

Injuries and adolescent ballet dancers:

Current evidence, epidemiology, and intervention.

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ABSTRACT

Background: It has been consistently reported in the literature that adolescent dancers have a high injury prevalence. Most injuries are reported as overuse onset and the most affected body region is the lower limb. Growth and maturation have been reported as non-modifiable whereas poor motor performance in power and strength as modifiable risk factors.

Methods: A systematic review was conducted to evaluate the association of growth, maturation and overuse injuries in aesthetic sports/disciplines. This was followed by a prospective cross-sectional study to assess the relationship of injury incidence and primarily countermovement-jump (CMJ), a valid indicator of motor performance, and secondarily gender differences and maturity status. Three randomized controlled trials (RCT) were conducted to assess 1) the feasibility of a trial in a vocational environment, 2) to conduct power and sample calculation and 3) to assess the effects a neuromuscular injury prevention intervention on countermovement-jump, reactive strength-index (RSI), isometric mid-thigh pull (IMTP) and inter-limb asymmetry (ASYM) in adolescent ballet dancers.

Results: The results from the systematic review were inconclusive, due to the heterogeneity of the studies, the research design, and sample size. The cross-sectional study revealed no association between injury incidence and CMJ; and there was no statistically significant gender or maturity status differences in injury incidence. The RCT results demonstrated no statistically significant between-group differences in the mean scores of all the measured parameters. Both groups revealed potentially clinically meaningful difference, between pre and post intervention scores in CMJ and IMTP. No harm was observed, however, less injuries were reported for the intervention group during the duration of the trial.

Conclusion: The results of this investigation indicate no association of CMJ and injury incidence, and no gender or maturity status differences in injury incidence were observed. The RCT results indicate no significant between-group post intervention differences in all the assessed parameters. The observations about the potentially clinically meaningful results in power and strength, may warrant further investigation in this area of study. Research in injuries and dance is particularly important, given the high prevalence, suggesting that more work is needed in this field to ameliorate the detrimental effects of injury in this population.

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LIST OF ABBREVIATIONS

(alphabetical order)

ACL	Anterior cruciate ligament
ASYM	Inter-limb asymmetry
BMI	Body mass index
CI	Confidence intervals
ClinInc	Clinical incidence
CMJ	Countermovement jump
CNS	Central nervous system
CT	Contact time
CV	Coefficient of variation
DJ	Drop jump
DOMS	Delayed onset muscle soreness
EQUATOR	Enhancing the QUALity and Transparency Of health Research
FIFA	Federation Internationale de Football Association
FT	Flight time
ICC	Intraclass correlation coefficient
IMTP	Isometric mid-thing pull
IOC	International Olympic Committee
IP	Injury proportion
IR	Incidence rate
IRR	Incidence rate ratio
LED	Light-emitting diodes
NT	Neuromuscular training
PAH	Predicted adult height
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
PHV	Peak height velocity
PNS	Peripheral nervous system
RCT	Randomised controlled trial
ROM	Range of movement
RSI	Reactive strength index
SD	Standard deviation
SE	Standard error
SLCMJ	Single-leg countermovement jump
TOST	Two One-Sided Tests
TRIPP	Translating Research into Injury Prevention Practice framework

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RESPONSIBILITIES AND SKILLS ACQUIRED

Responsibilities	Skills acquired
<hr/>	
<ul style="list-style-type: none">▪ Conduct and submit for publication a systematic review▪ Study design and methodology of the studies of this thesis▪ Obtain ethical approval▪ Recruitment▪ Data collection▪ Data analyses, with the assistance of George Metsios and Ian Lahart▪ Data interpretation▪ Write up of the thesis▪ Presentations in scientific conferences▪ Dissemination of findings	<ul style="list-style-type: none">• Knowledge on how to conduct systematic reviews and assess bias• Knowledge in growth and maturation• Knowledge in epidemiological reporting• Knowledge in neuromuscular training• Development and execution of testing protocols• Knowledge in conducting randomised controlled trials• Writing and presentation skills• Knowledge in the creation of mobile device applications• Knowledge in internet site development• Knowledge in video production

1 Introduction

Injuries can have negative consequences on the health and performance of the young dancer (Krasnow et al., 1999), as they may limit exposure from class and consequently hinder artistic development (Kenny et al., 2016). Compared with other adolescent sport population, pre-professional dancers show similar injury rates but higher risk (76%) of injury with 72% of the reported injuries being due to overuse (Ekegren et al., 2014). Sixty-six to 91% of all injuries are at the lower limb (Smith et al., 2015).

Literature studies in this field of investigation have identified several risk factors for injuries, but evidence is inconclusive (Jacobs et al., 2012). Injury risk factors can be classified as non-modifiable or extrinsic and modifiable or intrinsic (Emery, 2003, DiFiori et al., 2014). A frequently observed non-modifiable factor identified in the literature is growth and maturation, and previous injuries (DiFiori et al., 2014), whereas some of the modifiable factors are considered to be poor endurance, strength, balance/proprioception and lack of pre-season preparation (Emery, 2003). In addition, high training volume, commonly seen in vocational dance education, has consistently been associated with increased overuse injury risk (DiFiori et al., 2014).

In vocational dance training, the focus of the training is developing artistry and movement proficiency. This highly specialised and repetitive technical skills environment is associated with increased risk of injuries in adolescents (Myer et al., 2015a). Young dancers may have accumulated hours of training per year prior to their entry in vocational education, however, there is no data available to justify this speculation. Upon entry, a young dancer of chronological

age 11+ years begins training 19 hours of structured classes. A recent longitudinal clinical case-control study suggests that adolescents who train more hours per week than their age are more likely to develop injuries and overuse injuries (Jayanthi et al., 2020). During this volume of training very little time is spend on developing physical abilities. It has been documented that the dance-only approach is not offering enough stimuli for physiological adaptations (Koutedakis and Jamurtas, 2004). In addition, the lack of diversification in the activities may not give the opportunity for appropriate neuromuscular skills that are effective in injury prevention (Myer et al., 2015a). Injury prevention programs with strength focus and neuromuscular control show to be effective in the reduction of injury risks, overall injury incidence (Lankhorst et al., 2012, Brunner et al., 2019) and performance enhancement in muscular strength and power (Hopper et al., 2017, Zarei et al., 2018, Ayala et al., 2017b, Rössler et al., 2016a).

Several studies have shown strong relationships between strength and power measures and jump height scores, in youth (Ashley and Weiss, 1994, Peterson et al., 2006), and elite sport (Wisløff et al., 2004). Assessing the jump-height, therefore, is an easy to record, reliable and valid method of power assessment (Taylor et al., 2010, Ramírez-Vélez et al., 2017). Jumping performance has been included in performance prediction equations in sports (Pienaar et al., 1998, Bencke et al., 2002). Even though such equations do not apply to an aesthetic discipline like ballet, where the aesthetic look of the jump is more important than the height of the jump, jumping is still an integral part of the ballet class and performance. It has been reported anecdotally that young elite ballet dancers perform more than 200 jumps per 1.5 hour of technique class. This indicates the need for power and muscular endurance (Koutedakis and

Jamurtas, 2004). The relationship of jump-height and injuries is not clearly demonstrated in the literature. Low quality studies with major methodological limitations make this relationship unclear (Moita et al., 2017). Despite the high injury rates reported over the past two decades in dance, research on injury prevention interventions in dance is scarce (Caine et al., 2015). Research studies with either hybrid interventions, individualised training programs (Allen et al., 2013, Bronner et al., 2018), or not reporting the training programs that were utilised (Mistiaen et al., 2012, Roussel et al., 2014), do not give a clear picture of how to use exercise and conditioning in order to manage or minimise the risk of injuries in dance. The review of the literature revealed a gap in injury prevention interventions in dance.

To address these matters, this research PhD project begins with a review of the literature (chapter 2), starting with a general introduction on dance and vocational dance education. It then discusses ballet as an early specialisation discipline and the relationship of early intensified training with growth, maturation, and overuse injuries. The review of the literature then focuses on injury prevention in sport and the utilisation of neuromuscular training for the reduction of injury incidence and concludes with the current state of the art in injury prevention in dance. Considering the negative effects an injury can have on the career of the young dancer, together with the psychological and financial costs associated with injuries, the overall aim of the thesis to investigate an injury prevention intervention for dancers that will contribute to the beginning of a new chapter in the literature.

The first study is presented in chapter 3; a systematic literature review on the association of growth and maturation and overuse injuries in aesthetic sports. This is the first systematic

review to investigate this association, the equivocal results of which, led to further investigations of the relationship of injury incidence with primarily the countermovement jump height and secondarily with maturation stage in elite adolescent ballet dancers was conducted at a vocational dance school in the United Kingdom (Chapter 4). The null hypothesis was that injury incidence would not be associated with countermovement jump or maturity status. This study is contributing in the literature of injuries and their relationship with physiological parameters but also the relationship of injuries with growth and maturation. The results of this study lead to a focus on neuromuscular training, as neuromuscular control has been identified as an associated risk factor for lower extremity injuries. Injury prevention research also suggests that neuromuscular training may decrease injury risk factors for both traumatic and overuse injuries.

In chapter 5, the theory behind neuromuscular training is discussed and the creation of a neuromuscular injury prevention intervention for dancers named “11+Dance” is presented. Chapter 6 presents a feasibility randomised trial on the utilisation of neuromuscular training with adolescent dancers. The aim of this study was to assess the intervention adherence and fidelity prior to further studies. One important finding from the feasibility study was that the introduction of any intervention should not be added as extra load in the schedule of the students but should be included within the given hours per week of training. The findings of the feasibility study guided the design of the randomised controlled pilot trial, on the effects of neuromuscular training on physiological parameters in adolescent dancers, with the main aim to perform power and sample size calculations, presented in chapter 7. Guided by the results of the pilot trial, the main randomised controlled equivalence trial is then presented in chapter

8. This trial was conducted to investigate the effects of neuromuscular training (11+Dance) on physiological parameters, such as countermovement jump height, reactive strength index, maximal lower body strength, and inter-limb asymmetry in the single leg countermovement jump in adolescent dancers. Since all the trials were conducted in the same centre, a few participants who volunteered in the pilot and the main trial were exposed to the intervention twice due to the randomisation process. For this reason, an exploratory subgroup analysis of all the participants who were exposed to the intervention for the first time. The hypothesis, methods, and results along with the clinical significance of the findings are discussed in detail in the relevant chapters. The strength and limitations of this investigation are presented in chapter 9 and the thesis concludes with the general discussion in chapter 10.

2 Review of the literature

2.1 Dance the art form

Dance can be defined as any patterned or rhythmic movement in space and time (Copeland and Cohen, 1983). Even though there are numerous styles of dance, dance can be mainly split to three genres, classical, modern and post-modern (Copeland and Cohen, 1983, Adshead-Lansdale and Layson, 2006). Classical ballet is an art-form based on rules of the school founded by Louis XVI (1638 – 1715), but ballet as we know it today originated from Russia (Crowle, 1958). The word originates from the Italian word *balletto* which means “little dance”, and became *le ballet*, which simply means dance (Audsley, 1960), when it was taken over by the French courts (Selby-Lowndes, 1981, Audsley, 1960). Ballet consists of five positions for the feet known as the first, second, third, fourth and fifth position (Audsley, 1960). These five positions were established officially as the principles of the classical technique by 1700 (Copeland and Cohen, 1983). Movement in ballet starts, ends or passes through from at least one of these five positions (Coplan, 2002). All five positions demand the feet to be in a *turnout* stance, which is the outward rotation of the legs and the feet (Gilbert et al., 1998, Negus et al., 2005). There are six ballet training method approaches worldwide, the Russian (Vaganova), Italian (Cecchetti), British (Royal Academy of Dance), French (Ecole Francaise), Danish (Bournonville) and the American (Balanchine) (Morris, 2003). In the U.K. students may choose to go through both the Royal Academy of Dance and Cecchetti certification. Participation in ballet for children and adolescents is difficult to determine as there is no

individual genre data available. Children's participation in dance activities was 29.4% for 5 to 10 years of age, and 37.5% for 11 to 15 years of age in 2016/17, down from 43.1% and 51.9% in 2008/9, respectively. Adult participation in ballet has been fluctuating between 0.3 to 0.7% between 2006 and 2016 and was estimated to be 0.6% in 2016. The share of people who participated in dance (not for fitness) in England between 2006 and 2016 has been between 7.9 and 9.7% and was estimated to be 7.9% in 2016 (Statista, 2018). Participation in dance can either be recreational, where dance is seen as an activity of fun, or vocational, where dance involves training that is specialised and intensified with the aim of a professional career (Mitchell et al., 2016). The dance sector is currently estimated to employ 30,000 people. Approximately 22,500 follow a dance teaching career, 5,000 are employed in a variety of dance support careers, such as management, therapy, and notation and only 2,500 are in performance (OneDanceUK, 2017).

2.2 Vocational education

Vocational training is a type of education that allows the student to prepare/train for a particular performing art through hands-on, practical experience and training. In performing arts, training may be specialised in music, musical theatre, drama, contemporary dance, or classical ballet, with enrolment and admission being done through audition. There are currently four independent dance boarding schools, two independent sixth form training dance schools and ten advanced training centres (Table 2-1) (GOV.UK, 2018).

Table 2-1. List of pre-18 years old and 18 years old vocational dance schools in the United Kingdom

Independent Boarding Schools (11-19 years old)	Royal Ballet School, London Tring Park School, Hertfordshire Elmhurst Ballet School, Birmingham Hammond School, Chester
6 th Form Independent Schools (16-19 years old)	English National Ballet School, London Central School of Ballet, London
Advanced Training Centres (varied age groups)	London Contemporary Dance School Laban Centre, London Dance City Academy, Newcastle Swindon Youth Dance Academy, Swindon, Wiltshire Yorkshire Young Dancers: Northern School of Contemporary Dance (Leeds) Yorkshire Young Dancers: Academy of Northern Ballet (Leeds) Dance East Academy (Ipswich, Suffolk) DanceXchange South Asian and Contemporary Dance CAT in Birmingham Dance4, Nottingham The Lowry, Salford Quays

Vocational training in dance can be taken at the secondary (≥ 11 years old), or post-secondary (≥ 16 years old) level. The aim of a vocational dance school is to produce dancers for a career in the industry. The secondary curriculum is usually built as a full-time eight-year training program (11 to 19 years of age) (Guidetti et al., 2008). The total training load in hours of dance of a vocational program that lasts eight years is approximately 6200 hours of scheduled classes (Figure 2-1). Hours that correspond to shows, or short-term seasonal schools, i.e. Christmas, Easter or Summer Schools are not included as the individual variability make it impossible to calculate.

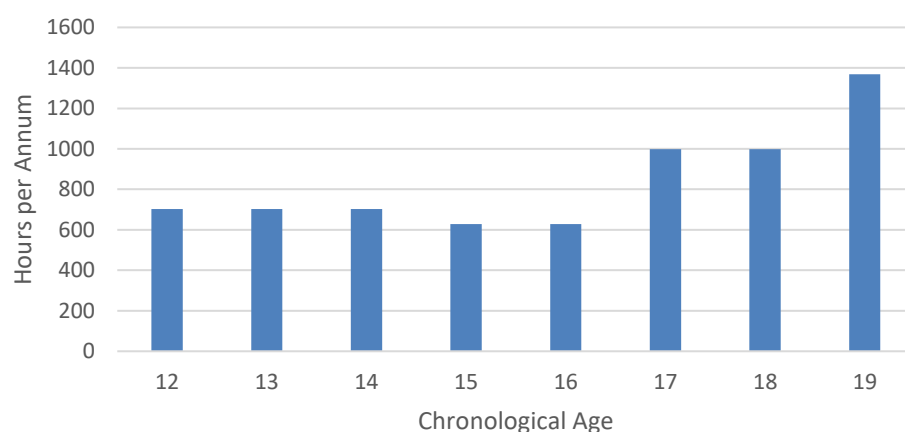


Figure 2-1. Vocational dance school annual dance exposure in hours

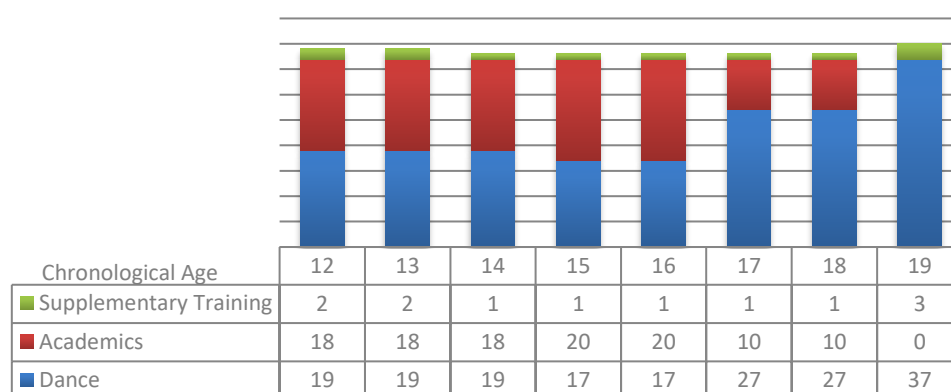


Figure 2-2. Vocational dance school weekly time (hours) allocation for dance training, academics and supplementary training in the U.K.

A vocational dance training program may range between 17 to 19 hours of a dance training per week in the first five years of training combined with academic studying and supplementary fitness training, whereas, in the last three years of training (16 to 19 years old) training may range between 27 to 37 hours of dance per week, with total 37 weeks of training in a year

(Ekegren et al., 2014, Gamboa et al., 2008, Whipple et al., 2004). Figure 2-2 indicates the weekly allocation of hours for dance training, academic lessons and supplementary training in a vocational setting in the U.K. This intensification of training at a young age together with the fact that a lot of young dancers may begin training in dance, and in particular ballet, as early as five years old are partly the reason why ballet is classified as an early specialisation discipline. Traditionally, early specialisation is considered vital to the success of the ballet dancer, however, research on youth development and talent identification in sports have indicated the pros and the cons of this approach in training (Jayanthi et al., 2013, Myer et al., 2015a). In the following section, a brief review of the concept of early specialisation is presented.

2.3 Early Specialisation

A recent consensus by the American Orthopaedic Society for Sports Medicine (AOSSM) defined early sports specialisation, or early single-sport/discipline specialisation by the following three criteria: 1) when participation in intensive training and/or competition in organised sports is greater than eight months per year (especially year round), 2) when participation in one sport is done to the exclusion of participation in other sports and overall there is limited free play, 3) when participation involves prepubertal (year 7 or roughly age 12 years) children (LaPrade et al., 2016). Early specialisation is based on the theory of deliberate practice, the type of training that involves effortful practice, with low levels of inherent enjoyment, and clear purpose of improving performance in the sport/discipline (Ericsson et al.,

1993, Ericsson and Charness, 1994, Myer et al., 2015b). It is argued that this deliberate practice should coincide with biological and cognitive development during childhood, in order for the early specialisation to lead to future success (Ericsson et al., 1993). Advocates of this concept in youth development suggest that early specialisation contributes to youth's detrimental experiences due to the volume, the intensity, and the pressure to perform in elite sport developmental structures. A diversification approach as an alternative is proposed with a focus on enjoyment in a variety of sporting activities during childhood (Côté and Hay, 2002). It is believed that early diversification can lead to excellence (Côté and Hay, 2002), as the developed skills and physiological conditioning may be transferable to the individual's later sport specialisation (Baker, 2003). In aesthetic sports/disciplines it is accepted, anecdotally, that elite performance relies on early-specialisation training (Malina, 2010, Smucny et al., 2015).

The relationship between youth and adult success in sport has been previously investigated (Barreiros et al., 2014, Durandt et al., 2011, Güllich and Emrich, 2006, Moesch et al., 2011). One third of athletes from soccer, swimming, volleyball or judo who competed internationally at pre-junior level (≤ 16 years) also competed at senior level (Barreiros et al., 2014). Durandt and colleagues found that 76% of the Under 13 players who competed a national level, did not compete at the Under 18 tournament in successive years (Durandt et al., 2011). Moreover, Kearney and Hayes in a prospective analysis of data for track and field athletes in the United Kingdom, show that less than 30% of the athletes who were ranked in the top 20 at Under 13 still had a national ranking at Under 20. Taken together these studies indicate that success at a young age is not a prerequisite for later success (Kearney and Hayes, 2018).

This intensification of training at a young age together with the fact that a lot of young dancers may begin training in dance, and in particular ballet, as early as five years old are partly the reason why ballet is classified as an early specialisation discipline. Traditionally, early specialisation is considered vital to the success of the ballet dancer, however, research on youth development and talent identification in sports have indicated the pros and the cons of this approach in training (Jayanthi et al., 2013, Myer et al., 2015a).

In dance, it has been reported that 65% of 960 dancers who responded in a national survey did not make it into a professional career, even though 90% did have the aspiration to do so (Hamilton, 1998). Attrition rates in vocational dance training, are estimated to be between 53% and 55% (Hamilton et al., 1997). Factors for this high rate of attrition are associated with normal age of menarche, anatomical limitations (lack of turnout) and musculoskeletal injuries (Hamilton et al., 1997), research, however, in adherence and dropout in the dance domain is lacking (Walker et al., 2012). In addition, research on deliberate practice and early specialisation or diversification in dance is scarce (Walker et al., 2010), since there is no development model specifically for dancers.

There have been several models of athlete development suggested in sport literature to explain long-term participation and performance in sport (Abbott and Collins, 2004, Côté et al., 2007, Stambulova, 1994). A youth physical development (YPD) model has been recently suggested by Lloyd and Oliver (2012), that covers athletic development from childhood (2 years old) up to adulthood (21+ years old). The YPD model offers a comprehensive approach to the development of young athletes depending on their gender, chronological and biological age

(Lloyd and Oliver, 2012). The National Strength and Conditioning Association has also published a position statement on long-term athletic development aiming to a) promote a more holistic approach of long-term athletic development, b) promote the lifelong benefits of healthy physical activity and c) prevent and/or minimise injuries from sport participation (Lloyd et al., 2016).

McGuine and colleagues reported that high school athletes who specialised in one sport were more likely to sustain a lower extremity injury than athletes who didn't specialise (McGuine et al., 2017). The development of chronic injury before the age of 18 years may lead to early retirement (Lewis et al., 1997). A recent systematic review (43 studies, n= 467,996 participants) on children's and youth's dropout from organised sport identified five main factors, lack of enjoyment, perceptions of competence, social pressures, competing priorities and physical factors such as maturation and injuries (Crane and Temple, 2015). Early sport participation and specialisation training is intensified during adolescence (Malina, 2010, Smucny et al., 2015), a period corresponding to the ages between 10 and 19 years old (World Health Organization, 1986). During this period adolescents go through a period of accelerated growth and maturation (Smucny et al., 2015, Engebretsen et al., 2010).

2.4 Growth and Maturation

Growth refers to changes that can be quantified, either in the size of the body or the size of specific body regions (Beunen and Malina, 2005). Growth also includes changes in body composition, physique and specific body systems (Malina, 1994). The pattern of growth in

terms of the size that is gained and rate, is similar for body mass and other dimensions except of fat mass and fat distribution (Beunen and Malina, 2005). During adolescence tissue maturation develops, non-linearly unequally (Hawkins and Metheny, 2001), and varies between individuals (Engebretsen et al., 2010). The ratio of muscle strength to body or limb mass and moments of inertia change, and soft tissues may experience more stress and strain that may result in decreased flexibility when the growth-spurt occurs (Micheli, 1983, Caine et al., 1989, DiFiori, 1999, Hawkins and Metheny, 2001, Malina et al., 2004). Beunen and Malina (2008), however, suggest that mean scores in the sit and reach test increase during adolescence and plateau at about 14-15 years in girls, whereas decrease from childhood to mid-adolescence and increase after in boys (Beunen and Malina, 2005). Interestingly, it has also been suggested that flexibility changes are not associated with the adolescent growth (Feldman et al., 1999, Ortega et al., 2011).

In contrast, maturation, refers to both functional and structural qualitative changes in the system of the body's progress towards a mature state. These changes can be soft or hard tissue, secondary sexual characteristics (e.g. pubic hair, breast development) appearance of menstruation (Malina et al., 2004, Beunen and Malina, 2005). Maturation involves all tissues, organs and systems of the body, but at different times and rates (Malina et al., 2004). In order to get an indication of the maturity status of the individual (i.e. the status at the time of the observation) outcomes of this process are observed, assessed and/or measured. Two biological maturation markers that are commonly used assessments are the skeletal age and the secondary sex characteristics (Bergeron et al., 2015b). Both represent the chronological age of an individual when a specific level of maturity of the hand-wrist bones, or the genitals was reached.

Skeletal age is always relative to chronological age as it has limited utility as an individual value (Malina, 2011). The chronological age when specific maturation events take place correspond to maturity timing, which is commonly assessed by age at peak height velocity (PHV) and age at menarche (Bergeron et al., 2015b). Both events take place during the adolescent growth spurt. During the spurt, growth rate, also referred as tempo, increases and reaches a peak (PHV) at about 12 and 14 years in girls and boys respectively (Beunen and Malina, 2005). Adolescence corresponds to the period approximately between the ages of 10 and 19 years old (Canadian-Pediatric-Society, 2003).

Growth and maturation are complex and dynamic processes that can be influenced by genetic and environmental factors (Thomis and Towne, 2006, Butte et al., 2007). Genetic predisposition to growth and environmental factors associated with growth are both interrelated as the genetic predisposition can only fully take place when the environmental conditions are favourable (Tanner, 1978). Environmental factors can either act independently or in combination to alter the genetic potential of growth of an individual (Georgopoulos et al., 2004). Growth parameters, such as height and weight are both dependent on genetics, however, weight, fat mass and fat distribution are more influenced by environmental factors, such as dietary intake and energy expenditure (Thomis and Towne, 2006). Even though the association of delayed menarche, with high levels of athletic performance is documented in female athletes (Clapp and Little, 1995), this concern is not proven. Small non-randomised studies with major methodological limitations, such as recruitment bias, either overestimate or underestimate the incidences (Redman and Loucks, 2005). It has been advocated that the association between athletic performance and delayed menarche may be solely due to genetic

preselection and socialisation. This view supports the notion that the individual who matures late may be more likely to have a linear physique and motor skills that are suited to athletic success, whereas the individual who matures earlier physical characteristics may affect physical performance negatively and encourage socialisation away from sports (Malina, 1983, Malina, 1994).

In sports/disciplines, such as gymnastics and ballet, where there is preference to an optimal somatotype, the strict control of energy intake together with high energy output during preadolescence and adolescence can affect secondary sexual maturation, such as breast development and menarche (Georgopoulos et al., 2004). It is suggested that growth may be compromised in sports/disciplines like gymnastics and ballet if energy intake is not increased beyond the needs of training (Pediatrics, 2000). Theintz and colleagues in a longitudinal prospective cross-sectional study suggest that intensive exercise (>15 to 18 hours per week) together with food restriction can affect growth potential (Theintz et al., 1993). Although the results have not been replicated by other studies yet, it is very difficult to have any conclusive evidence from such research protocols. On the contrary, other cross-sectional studies of adolescent female (Bass et al., 2000) and male gymnasts (Daly et al., 2000), reported no relationship of short stature for both female and male gymnasts or menstrual irregularities with gymnastics training.

Caine and associates through the presentation of case reports, cross-sectional and longitudinal studies state the difficulties in identifying causation in the relationship of growth and maturation and intensified training but also suggest that the combination of intensified training

and poor nutrition may be associated with growth reduction, delayed maturation and growth plate injuries (Caine et al., 2003). More recent reports also suggest that intensified training in combination with suboptimal energy intake during adolescence may potentially be associated with serious health issues, such as relative energy deficiency syndrome (Mountjoy et al., 2014), burnout (Matos et al., 2011) and overuse injuries (Thein-Nissenbaum et al., 2011).

2.5 Overuse Injuries

During sport participation anatomical structures incur microtrauma due to repetitive loading. Sufficient recovery between exposures allows the tissue (bone, muscle or tendon) to remodel and adapt to the applied stress (DiFiori, 2010a). This microtraumatic damage can develop an overuse injury due to the repetitive submaximal loading and/or insufficient time to heal or undergo the natural reparative process (Brenner et al., 2007, Adirim and Cheng, 2003, DiFiori, 2010a). Load is *“the sport and non-sport burden as a stimulus that is applied to a human biological system”* (p.1031) (Soligard et al., 2016). For the purposes of this thesis, load will be referring to *“external load”*, i.e. a stimulus that is applied to the individual that is measured independently of their individual characteristics. This can be applied over different time periods (seconds to years) and with different levels of duration, frequency and intensity (Soligard et al., 2016). A recent systematic review of longitudinal studies (68 studies) suggests that there is evidence for the relationship between training load and the occurrence of illness, traumatic and overuse injury (Jones et al., 2016).

Overuse injuries are not characterised by acute inflammation, instead degenerative changes prevail (DiFiori, 2010a). When the term *overuse* is used as the mechanism of injury, it refers to the cause of the injury, i.e. the repetitive or cumulative activity or load (Meeuwisse et al., 2007, Knobloch et al., 2008). On the contrary, when the term is used as a diagnosis, it often refers to a group of injuries characterised by slowly progressing inflammation, pain and loss of function (American Academy of Pediatrics and Fitness, 2000, Cuff et al., 2010). Overuse, therefore, as a mechanism is the cause, whereas, as a diagnosis is the effect of the injury (Roos and Marshall, 2014).

Risk factors can be divided into intrinsic, extrinsic (Lysens et al., 1984), modifiable and non-modifiable (Bahr and Holme, 2003). Intrinsic factors are biologic and psychosocial characteristics that predispose the individual to an injury (e.g. previous injury, life stress, menstrual dysfunction) (Bahr and Holme, 2003, Caine et al., 2008, DiFiori, 2010a, Bowerman et al., 2015a). Extrinsic factors, follow predisposition, as they are the “enabling” factors that may facilitate the manifestation of an injury (Meeuwisse, 1994). These are factors that may affect the individual during participation in the sport/discipline (e.g. training technique, equipment) (DiFiori, 2010a, Bowerman et al., 2015a). Modifiable risk factors are the factors that can be changed, whereas non-modifiable are those factors that cannot be altered (Caine et al., 2008). A systematic review (45 studies, n= >500,000 participants) on risk factors for injuries in child and adolescent sport found some evidence that poor endurance, strength, balance/proprioception, lack of pre-season training and some psychosocial factors (e.g. socioeconomic status, stress level, fatigue) were potentially modifiable risk factor. On the

contrary, non-modifiable factors were identified consistently in the literature to be age, gender and previous injury (Emery, 2003).

DiFiori and colleagues, stated that there is little research with a specific focus on the incidence and prevalence of overuse injuries in children and adolescents (DiFiori et al., 2014), however, high incidence of overuse injuries in adolescents in sport is reported in a number of studies (Dalton, 1992, Baxter-Jones and Helms, 1996, Caine et al., 2006b, Caine et al., 2008, Baker et al., 2009, DiFiori, 2010b, DiFiori et al., 2014, Kox et al., 2015a). Estimates of overuse injuries in sports range from 45.9% to 54% (Watkins and Peabody, 1996, Luke et al., 2011, Valovich McLeod et al., 2011), though, such injuries are underestimated over acute injuries mainly because most epidemiological studies define injury as time loss from participation, which in many overuse injuries is not always the case (Bahr, 2009, Yang et al., 2012). In particular, overuse injuries prevalence in youth skiing and handball was 37% (Bergstrom et al., 2004, Moller et al., 2012), in recreational and competitive running 70% (Hreljac, 2004, Ferber et al., 2009) whereas in high school runners at 68% (Tenforde et al., 2011).

In aesthetic sports/disciplines overuse injuries have higher prevalence than acute injuries. More specifically, these are 64.4% in gymnastics (Caine et al., 1989), 72.7 and 68.5% in female and male singles respectively and 44.1% overall in figure skating (Dubravcic-Simunjak et al., 2003). In aquatic sports overuse injuries are higher than acute injuries (37.5%) (Mountjoy et al., 2010), however there is no study with a clear distinction between the aesthetic sports and the rest of the aquatic sports.

Numerous epidemiologic studies have been conducted on dance injuries over the past two decades reporting injury incidence of 40% to 80% depending on the level of participation (Bronner and Brownstein, 1997, Wiesler et al., 1996, Allen et al., 2012, Caine et al., 2016) and overall lifetime incidence of up to 90% for all dancers (Macintyre and Joy, 2000). Compared with other styles of dance, classical ballet has the highest prevalence of overuse injuries, in comparison with Spanish dance, neoclassical and contemporary. The rigid restricted technique of classical ballet, the nature of the teaching system that is based on high repetition of moves and/or the lack of sufficient rest between these repetitions may all play a major part to this high prevalence of overuse injuries (Sobrino et al., 2015). Smith and colleagues in a recent systematic review (19 studies, n= 2617 participants) on the prevalence and profile of musculoskeletal injuries in ballet dancers point out that the results that the data suggest the injury patterns are similar between professional and pre-professional ballet dancers (Smith et al., 2016).

In professional ballet dancers 68% for females and 60% for males (Allen et al., 2012) and 76% in pre-professional dancers (Ekegren et al., 2014). An annual estimation of over 22,000 injuries related to dance seen in emergency departments in the United States (Roberts et al., 2013). Van Mechelen and colleagues, however, stated that there is a risk of under-estimation if epidemiology relies on insurance files and data from medical channels. This is because a large percentage of serious acute injuries do get observed and recorded whereas less serious overuse injuries may not be recorded (Van Mechelen et al., 1992).

In pre-professional ballet and contemporary dancers most injuries get reported to the lower extremity (79.5%), with the five most frequently injured locations being the ankle (24.2%), foot

or toe (19.5%), hip or thigh (15.4%), back (13.5%), and knee (13.0%). Most injuries were the result of overuse (67.9%) (Yau et al., 2017). Similarly, Caine and colleagues reported the lower extremity to be the most affected body region by injury (85.96%) in pre-professional ballet dancers, with the majority of the injuries (65.8%) being gradual onset or overuse, with 54% of those injuries being recurrent ones (Caine et al., 2016). Importantly, Jacobs and colleagues in a systematic review (29 unique studies) on musculoskeletal injury and pain in dancers, pointed out the lack of quantity and quality in the available studies. The heterogeneity of studies together with the methodological flaws in injury definitions and monitoring, made it difficult to have any conclusive evidence on the risk factors of injuries in dance (Jacobs et al., 2012). Similar to sports, however, previous injury, is one of the associated risk factors for an overuse injury in dance (Luke et al., 2002, Bronner et al., 2003, Gamboa et al., 2008, Allen et al., 2012), whereas, the association of growth and maturation with overuse injuries is unclear and will be discussed in more details in the following sections.

2.6 Growth, maturation, and overuse injuries

A recent prospective cross-sectional study in talented soccer players ($n = 26$), suggests that growth and maturation are potential risk factors for sport injuries. In particular, during the period of PHV adolescent soccer players seem to be more vulnerable to traumatic injuries, whereas, after the period of PHV there is an increase in the susceptibility of overuse injuries (van der Sluis et al., 2015). Johnson and colleagues in a six year prospective study in elite schoolboy soccer players found that skeletal age is an injury factor (Johnson et al., 2009). Increase in

growth-related overuse injuries and in the severity of the traumatic injuries in adolescent soccer players is also reported in older cross-sectional (Andreasen et al., 1993) and cohort studies (Le Gall et al., 2006). Simpson and colleagues in a systematic review (17 studies) on the age children and adolescents develop lower limb tendon pathology or tendinopathy indicate that they coincide with the ages of puberty and biological maturation (Simpson et al., 2016). Kox and associates in a systematic review (11 studies, n= 1529 participants) on wrist pain in young athletes found that age between 10 and 14 was strongly correlated with wrist pain with an odds ratio of 11.5, suggesting that during the growth spurt there is higher risk of overuse wrist injuries in young athletes (Kox et al., 2015a). An association between age range and wrist pain in young gymnasts has also been suggested (DiFiori et al., 2002).

Growth and maturation have been consistently associated with overuse injuries in adolescents (DiFiori, 1999, Caine et al., 2008, DiFiori, 2010a). Epidemiological studies (Caine et al., 1989), systematic (Kox et al., 2015a) and narrative reviews (Maffulli et al., 2011a, Caine et al., 2014, Feeley et al., 2015, Myer et al., 2015a, Martínez-Silván et al., 2016, McKay et al., 2016) indicate that during this period of accelerated growth, adolescent athletes are more susceptible to overuse injuries.

When planning for children's and adolescents' training and development it is important to keep in mind that children's anatomy and physiology is different to that of the adolescents' which in turn differs from the anatomy and physiology of the adults. For this reason it is commonly said that "*children are not miniature adults*" (Lloyd et al., 2016). The varying interactions of growth,

maturation and training make the development of skill and physical fitness is a complex and dynamic issue (Lloyd et al., 2014b).

2.7 Physical Fitness

Physical fitness is the functional state of the slow changing physiological components that relate to a specific motor ability. Physical fitness is comprised by many different qualities such as cardiovascular endurance, flexibility, and strength (Siff, 2003). Motor function is a combination of skill and ability (Kurz, 2001), the expression of which depends on the specific characteristics of the sport/activity. As in the case of most sports, fitness for ballet is characterised by a combination of all the above parameters.

2.7.1 Fitness for Ballet

Classical ballet can be classified as a high intensity intermittent exercise similar to football or tennis, followed by moments where the dancer needs to perform movements with precision and neuromuscular control (Twitchett et al., 2009b). The focus of ballet training is to master the art form by increasing the movement vocabulary of the dancer, improving musicality (Krasnow and Chatfield, 1996) and overall dancing proficiency. A ballet class, typically lasting between 90 to 120 minutes, is split into three main sections starting with low intensity work, at the *barré* which is generally considered the warm up where dance exercises are performed whilst holding on to a bar that is grounded on the floor (Rodrigues-Krause et al., 2014b). The *barré* concludes with ballistic movements of the legs (*grand battement*) and static stretching for the lumbar spine, and hips. This is followed by medium intensity work, at the *centre*. This work

starts with standing dynamic stretching of the upper body, while the lower body is static (*port de bras*) and concludes with action that involves spinning on one leg (*pirouettes*). The class generally concludes with high intensity work, (*allegro*) which is a series of jumps that could be subdivided in the small jumps (*petit allegro*) and the big jumps (*grand allegro*) (Wyon et al., 2004, Wyon, 2005, Twitchett et al., 2009b). The structure of the class follows the same pattern in a vocational education setting, however the difficulty of the tasks/exercises is regressed or progressed depending on the chronological age of the student.

2.7.2 Aerobic (cardiorespiratory) fitness

Cardiorespiratory fitness, also called cardiovascular fitness/endurance, or maximal aerobic power refers to the ability of the individual to perform muscular work under aerobic conditions, involving all aspects of uptake, transport and oxygen utilisation to free energy from muscle fuels (Koutedakis and Jamurtas, 2004). The assessment of the cardiorespiratory fitness is through the utilisation of a criterion measure, the maximal oxygen uptake (%VO₂max). VO₂max is the maximum rate at which oxygen can be consumed by the individual at sea level (Cardinale et al., 2011). The assessment of VO₂max can be performed with maximal or sub-maximal tests, by direct or indirect methods (Ortega et al., 2008).

In professional ballet dancers, the different parts of a class correspond to different %VO₂max values. At the *barré* the corresponding value has been reported to be 36% of maximum, whereas for the *centre* and *allegro*, 43% and 46% respectively (Schantz and Åstrand, 1984). Similar values have also been reported in pre-professional ballet dancers (Baldari and Guidetti, 2001). Compared to triathlon athletes (72% VO₂max) (Millet et al., 2003), soccer (58%), hockey

(58%) (Aziz et al., 2000), rhythmic gymnastics (50%), artistic gymnastic (50%) (Baldari and Guidetti, 2001), the ballet dancers demonstrate lower VO_2max values.

In addition, when compared with contemporary dancers, professional ballet dancer have lower values (Cohen et al., 1980, Chmelar et al., 1988), and are close to values of sedentary individuals of the same age (Koutedakis and Jamurtas, 2004). In ballet training, unlike other sports, aerobic fitness and skill development seem to develop independently and not in parallel with their careers possibly due to the dance-only training system approach (Koutedakis and Jamurtas, 2004). Moreover, it has been reported that, in professional dancers, the small aerobic increments measured are not related to the class work but to the length and number of their performances (Kirkendall and Calabrese, 1983).

2.7.3 Anaerobic fitness

During either the class, the rehearsal or the performance, the dancer is required to perform explosive jumps (*sissonne*, or *grandé jeté en tournant*) which last a few seconds. These jumps mainly get energy from the breakdown of phosphocreatine in the stored muscles (Koutedakis and Jamurtas, 2004), this energy source is also known as the alactic capacity (Bishop and Spencer, 2011). However, this energy system seems to be utilised during rehearsals and not during classes (Rodrigues-Krause et al., 2014b), as it has been shown that ballet exercises in class, according to VO_2 responses, are between low and moderate aerobic intensities and not anaerobic (Rodrigues-Krause et al., 2014a). The other anaerobic requirement occurs when power output in the form of multiple jumps, needs to be maintained for 30 to 60 seconds (Twitchett et al., 2009b), and is powered mainly from the breakdown of glycogen to lactate

(Hermansen and Vaage, 1977). Put together, the total anaerobic energy release or anaerobic capacity, can be defined the maximal amount of energy that can be released anaerobically during exhaustive, short duration bouts of exercise (Medbo et al., 1988).

Similarly, with the aerobic fitness the anaerobic values in professional dancers are lower than university ballet dancers and contemporary training and professional dancers. Mean peak blood lactate level was $6.0 \text{ mmol} \pm 1.5$ for the professional ballet dancers, whereas university ballet dancers demonstrated a mean level of $9.5 \text{ mmol} \pm 0.9$ (Chmelar et al., 1988). Methodological limitations due to the fact the researchers utilised the Wingate test (bike), together with the fact that it has been reported that dancers produce larger blood lactate levels with a running (treadmill) protocol (Schantz and Åstrand, 1984) make the results less reliable. Interestingly, a ballet class was reported to produce a mean lactate blood level of 3 mmol/L in female dancers, but a solo part in a choreography produced 10 mmol/L (Schantz and Åstrand, 1984), however, the use of the portable Douglas bag may be affecting the reported values, due to the fact that it restricts the movement of the dancer. The reported value, however, is similar to a professional football (McMillan et al., 2005), or tennis player (Fernandez-Fernandez et al., 2009). This not only suggests that the ballet class is not demanding enough for effective preparation of performance but is also indicating the need for the dancer to be able to tolerate this type of exercise. In addition, Twitchett and colleagues suggest that even though the physiological demands of a ballet performance do not change dramatically with different repertoire, these demands are different between the ranks of the company. Soloists performed more jumps but had the highest work to rest period, artists the longest time of work, with varying intensities (light, moderate and high), whereas principals worked at moderate or high

intensities with the lowest periods of rest. The authors highlight the importance of differentiation between the ranks but also gender when preparing for a performance (Twitchett et al., 2009a).

2.7.4 Flexibility

Flexibility refers to the measure of the maximum range of movement (ROM) a joint is capable of (Siff, 2003). This definition, however, does not include the notion of motion but rather the range is determined from a beginning and end (Sands, 2011), therefore, flexibility can be defined as the freedom of movement, the capacity of a joint to move with fluidity through its full range of movement (Metheny, 1952, Heyward, 1984).

In dance, extensive range of movement at the joints is a requirement for the effortless execution of moves during a choreography (Deighan, 2005). These joint positions include, hip flexion, extension and outward rotation, spine extension and extreme ankle planar flexion (pointing of the foot) (Deighan, 2005). Range of movement can either be passive or active (Wyon et al., 2013). An example of active flexibility in dance is the height of the leg in the position *développé á la seconde*, which involves a combination of an active end-of-range hip flexion with external rotation and abduction. This position is considered to be a prerequisite in professional dancers (Grossman and Wilmerding, 2000). Wyon and colleagues reported an association between leg length and active flexibility (*développé*) between undergraduate and professional dancers, highlighting the importance of strength in active flexibility in dancers (Wyon et al., 2010). Research has also indicated that active ROM can predict dance performance better than passive particularly in contemporary and ballet dance (Angioi et al., 2009, Twitchett et al., 2009b).

The utilisation of the sit-and-reach flexibility test to assess hamstring and low back flexibility is commonly used in middle-aged adults (Lemmink et al., 2003), young adults (Baltaci et al., 2003) adolescents (Castro-Piñero et al., 2009) and athletes (Muyor et al., 2014). This test, however, is not relevant to dancers as they are known to have large ROM (Klemp and Learmonth, 1984, DiTullio et al., 1989, Chatfield et al., 2014). The use of goniometers and photography is therefore suggested to be a more appropriate method to assess both passive and active ROM for dancers (Wyon, 2007).

2.7.5 Muscular Strength

Muscular strength is an important element of health in adults (Ruiz et al., 2008b, do Amaral Benfica et al., 2018) in children and adolescents (Faigenbaum et al., 2001, Benson et al., 2006, Ruiz et al., 2008a, Padilla-Moledo et al., 2012) but also for athletic performance (Myer et al., 2013a, Lloyd et al., 2014a, Suchomel et al., 2016). Muscular strength *is defined as the ability of a given muscle or group of muscles to generate muscular force under specific conditions* (p. 1) (Siff, 2003). Force is defined *as an instantaneous measure of the interaction between two bodies* (p.21) (Zatsiorsky and Kraemer, 2006). Muscular contraction produces internal tension, whereas force may be produced through resistance exercises, a partner or opponent, friction and/or gravity (Hartmann and Tünnemann, 2000). The magnitude of strength may range from zero to maximum (Stone et al., 2003), and it may occur with zero velocity (isometric strength) or a variety of velocities (dynamic strength), depending on the resistance that is being overcome (Stone, 1993). In isometric muscular action, there is force production, but no movement or work is performed. In dynamic muscle action there is concentric movement, where the muscle shortens, and eccentric movement where the muscle lengthens (Komi, 2008). Human

movement is rarely performed through isolated concentric, eccentric or isometric muscle actions. In many situations (e.g. running, jumping) eccentric action precedes the concentric action. This natural combination of muscle action is called *stretch-shortening cycle* (SSC) (Norman and Komi, 1979, Komi, 1984). This coupling of muscular contraction generates a more powerful contraction than the one a purely concentric contraction would generate (Flanagan and Comyns, 2008).

Muscular strength can manifest itself as maximal strength, muscular endurance, and power (Hartmann and Tünnemann, 2000). Maximal strength refers to the maximum load (or other external resistance) that an individual can perform one repetition (1RM) of a given exercise (Stone, 1993, Hartmann and Tünnemann, 2000). Muscular endurance refers to the ability to perform many repetitions of an exercise with a given resistance for a prolonged period of time (Komi, 2008). Muscular power is defined as the rate of the mechanical work performed or as the product of force and velocity (Adams et al., 1992, Stone et al., 2003, Harris et al., 2007, Fleck and Kraemer, 2014). Muscular power is the ability of the neuromuscular system to produce the greatest possible velocity of movement against gravity or as a result of applied force against a given resistance (Schmidtbleicher, 1992).

An increase in power makes the production of the same amount of work of a given muscle or group of muscles faster, or the magnitude of the work greater (Peterson et al., 2006). Muscular peak power is the maximal potential product of strength and speed and is demonstrated as the highest power output possible during a given movement (Komi, 2008). Stone and colleagues examined the relationship between maximal strength (1RM Squat) and power output (vertical

jump). The results of their study suggest that improvements in maximal strength could improve peak power output, i.e. improve jumping height (Stone et al., 2003). This is further supported through research in elite athletes (McBride et al., 1999, Nuzzo et al., 2008), soccer players (Wisløff et al., 2004), and young athletes (Peterson et al., 2006). In general, muscle strength and power have been considered as valid predictors of jumping performance (Baker et al., 2001, Cronin and Sleivert, 2005).

Like in sport, it is important for dancers to be able to produce high levels of muscle tension, i.e. muscular strength (Koutedakis et al., 2005). Lower extremity strength in particular is important not only for the bilateral and unilateral jumps that the dancers have to perform, but also because of the need to balance dynamically on one leg either to turn or perform a balletic position such as *arabesque* or *attitude* (Bennell et al., 1999). Strength training and the development of strength in general away from the studio has not been a necessity for a dancer's career (Koutedakis and Sharp, 2004). On the contrary the unsubstantiated fear of hypertrophy, loss of flexibility and the aesthetic look count as the main factors why strength training is not part of dance training (Koutedakis et al., 2005). It is, therefore, not surprising that research has revealed relatively low muscular strength levels in dancers compared to other athletic populations.

One of the earliest studies investigating muscular strength in dancers (mean age males= 24.6 ± 3.4 , females= 23.8 ± 3.9 years), found that when the isokinetic values were normalised for bodyweight male dancers reported 98% and females 77% of the weight-predicted strength values whereas athletes met and surpassed the criterion (Kirkendall et al., 1984). Even though

these normative values were originally set for male football players, Reid later suggested that these scores may have been key to some of the knee problems young dancers experienced (Reid, 1988). A study by Kuno and colleagues also revealed that female ballet dancers (mean age = 26.5 ± 4.4 years) with dancing experience of 20.4 ± 2.4 years, showed no significant differences in maximal isometric and isokinetic strength of quadriceps and hamstrings in absolute values when compared to sedentary females. There were some significant differences in the quadriceps, however, when the scores were divided by the dancers' bodyweight. In addition, there was no significant difference of either absolute or relative maximal voluntary contraction in plantar flexion for the dancers, but there was larger plantar flexion muscular endurance ($p < .01$). Considering that female ballet dancers during pointe work constantly perform plantar flexion, the authors suggested that the pointe work in ballet may not produce strength gain adaptations but does produce muscular endurance (Kuno et al., 1996). A 12-week strength training intervention study with professional ballerinas revealed that the experimental group felt better about their physical appearance and performance post intervention. The authors speculated that the dancer were performing at lower strength levels than the optimal before the intervention (Koutedakis and Sharp, 2004). Moreover, Harley and colleagues found that female dancers had greater quadriceps muscle strength than physically active controls but did not jump higher. The authors reported that the female dancers had similar force output with the controls, but with less electromyographic activity during squat, countermovement and drop jumps, potentially due to the fact that dancers may be sacrificing power output for aesthetics, or due to training-induced differences between the dancers and the controls in the elastic properties of the myotendinous tissue (Harley et al., 2002). Furthermore, it has been reported

that female adolescent ballet dancers had similar isokinetic lower extremity muscular strength with basketball players but generated lower levels of peak power compared to the basketball players (Kenne and Unnithan, 2008).

Research has previously suggested that certain forms of dance produce limited stimuli for fitness enhancement (Koutedakis and Sharp, 2004, Koutedakis et al., 2007, Wyon et al., 2002). Research also suggests that when the neuromuscular system is loaded sub-optimally there may be strength decrease both in males and females (Häkkinen, 1992), making the case for supplementary strength training for dancers stronger.

2.7.6 Assessment of muscular strength and power

Neuromuscular performance of the lower limbs can be measured isometrically or dynamically (Stone, 1993, Dos' Santos et al., 2017). Isometric strength assessment consists of maximal contractions by the athlete against immovable resistance (Cardinale et al., 2011). The isometric midthigh pull (IMTP) has often been used to assess isometric strength (Nuzzo et al., 2008, Thomas et al., 2015) and has demonstrated high within- and between-session reliability for peak force (Comfort et al., 2015, De Witt et al., 2018, Dos' Santos et al., 2017). The IMTP is time efficient and causes minimal fatigue in comparison with dynamic 1RM testing (Dos' Santos et al., 2017), but shows nearly perfect correlations with the 1RM back squat performance in recreationally trained men ($r \geq 0.96$) (McGuigan et al., 2010), college wrestlers ($r \geq 0.97$) (McGuigan et al., 2006), and 1RM deadlift performance in adult mixed trained population ($r \geq 0.88$) (De Witt et al., 2018).

Dynamic strength (power) can be measured eccentrically, concentrically or plyometrically. Plyometric is a term used to describe movements that are quick and powerful, using a pre-stretch or countermovement, i.e. involve the SSC (Potach and Chu, 2000). It has been suggested that the SSC can be either slow or fast. The fast SSC has short contraction times (< 0.25 seconds) and small angular displacements of the hips, knees and ankles (e.g. drop jump) (Schmidtbleicher, 1992). The drop jump is a plyometric exercise where the athlete drops from a predetermined height and immediately on landing pushes-off for a maximal vertical jump (Bobbert, 1990, Healy et al., 2016).

A fast SSC exercise like the drop jump can be used to assess the ability of the athlete to change quickly from an eccentric to concentric contraction can be assessed (Young, 1995), via the reactive strength index (RSI) (Wilson et al., 1991). The RSI is derived from the jump height (JH) in the drop jump and the contact time (CT) i.e. the time the athlete spends on the ground before the jump ($RSI = \frac{JH}{CT}$) (Flanagan and Comyns, 2008, Young, 1995). The JH, CT and RSI have demonstrated high trial-to-trial reliability ($ICC_{single} > 0.9$) (Flanagan et al., 2008).

On the contrary an example of slow SSC plyometric exercises include box jumps horizontal and vertical jumps (Flanagan and Comyns, 2008). The vertical jump is one of the ways peak power can be assessed (Owen et al., 2014) plyometrically (Meylan et al., 2011, Nuzzo et al., 2008, Owen et al., 2014) which over the years has been utilised in different variations (static or countermovement) (Newton U. R., 2002, Canavan and Vescovi, 2004, Ziv and Lidor, 2010). A static jump or squat jump (SJ) starts from static semi-squatted position with no downwards, countermovement, action before the maximal vertical jump (Bobbert et al., 1996). On the

contrary, in the countermovement jump the athlete lowers the centre of mass and then pushes-off for a maximal vertical jump, (Bobbert, 1990), either with an arm swing upwards or with the hands akimbo (Slinde et al., 2008). The CMJ has been shown to have very high reliability (ICC= 0.93, 95% CI 0.85 – 0.96) (Slinde et al., 2008). It has been argued that the maximum vertical jump height is a valid measure of the maximum power output of the lower limb musculature (Baker et al., 2001, Markovic and Jaric, 2007, Samozino et al., 2008), in populations of different age, gender and training status (Asmussen and Bonde-Petersen, 1974, Davies et al., 1984, Taylor et al., 2010, Castagna and Castellini, 2013, Laffaye et al., 2014, Holden et al., 2015). The vertical jump has been used as a power assessment in professional (Wyon et al., 2007), adolescent recreational male (Pekkarinen et al., 1989) and female (Claessens et al., 1987, Twitchett et al., 2010) ballet and female contemporary (Angioi et al., 2009) dancers.

In addition, the single-leg CMJ (SLCMJ) can be utilised to assess the inter-limb asymmetries, where the performance of the one limb is compared with the performance of the other (Keeley et al., 2011). Inter-limb asymmetry in the lower limb has been associated with injury and can be used as a predictive tool for detection of injury and re-injury risk in athletes (Paterno et al., 2007, Schiltz et al., 2009). Differences greater than 10-15% have been shown to be the threshold of increased risk of injury (Hewit et al., 2012, McElveen et al., 2010), whereas, differences of below 15% in the SLCMJ have been suggested as the physiological norm in youth (Ceroni et al., 2012, Fort-Vanmeerhaeghe et al., 2015). The SLCMJ has demonstrated excellent reliability (ICC= 0.99, 95% CI 0.97 – 0.99), in comparison with the single-leg hop (ICC= 0.81 – 0.88, 95% CI 0.64 – 0.95) the single-leg triple hop (ICC= 0.86 – 0.92, 95% CI 0.76 – 0.96)

and the crossover hop (ICC= 0.83 – 0.94, 95% CI 0.67 – 0.98) (Bishop et al., 2018). Bishop and associates suggest that the SLCMJ is the most appropriate jump test to identify between-limb asymmetries. They also suggest that horizontal jumping is not related to vertical asymmetries and vice versa (Bishop et al., 2018), supporting further the research that suggests that unilateral jumping performance is direction specific (Murtagh et al., 2017). The authors conclude that the SLCMJ differences were the only scores that were associated with sprint decrements, however, their study was limited to female soccer players (Bishop et al., 2018).

In dance, Golomer and colleagues utilise the SLCMJ test, however, they produced two papers with a small sample (n= 10) from the same dataset and reported contradicting results. In the one paper they suggest that the dance class develops symmetrical power for the female ballet dancer (Golomer and Féry, 2001), whereas in the second paper they suggest a relationship between the SLCMJ height and leg muscle mass in Opera female ballet dancers. Their results suggest a functional asymmetry and the effect of laterality (dominant leg versus non-dominant) in dance (Golomer et al., 2004), therefore, their results should be considered with caution. One recent study by Ambegaonkar and associates suggests that lower extremity horizontal work but not vertical power can be used to predict lower extremity injuries in collegiate dancers (Ambegaonkar et al., 2018), however, the researchers report that their study results may be affected by confounding factors and detection bias. The horizontal work was assessed with a unilateral jump [single-leg hop (SLH)], whereas the vertical power was assessed with a bilateral jump (CMJ with arms swing). Even though the authors were not comparing the two tests, it is unclear whether the superiority in the sensitivity of the SLH as a risk factor for injuries, is specific to the exercise (single versus two legs) or the direction of work. The authors identified

that dancers with scores that below 78.2% of their height may have increased probability of a lower extremity injury. The study, however, was conducted with no a priori power calculation, therefore, considering the small sample ($n=43$), the short duration of the study (16 weeks) and the lack of the participants' injury history, their results cannot be generalised (Ambegaonkar et al., 2018). Further prospective studies are needed to assess whether power performance exercises are associated or can predict injuries in dancers. Furthermore, Moita and colleagues in a recent systematic review (8 studies, $n=491$ participants) suggest that higher horizontal and vertical jump scores may not represent power-related strength in dance, but simply better intermuscular coordination for force production. They further suggest that jump power adaptations are task and skill specific and, therefore, have low transfer from one task to another (Moita et al., 2017). Skill specific adaptations or specificity in training refers to a principle that aims to secure optimal adaptation performance improvement (Siff, 2003, Reilly et al., 2009). In the case of dance, similar to other aesthetic disciplines like gymnastics or synchronised swimming, however, locomotion involves moves without a specific target, i.e. these movements are body-centred and have no goal in the environment (Latash, 2012a), other than aesthetic. This together with the fact that there is vast variety of jumps in dance, specificity in power testing and training becomes problematic and questionable.

Interestingly, since performance in dance is not driven by measurable values, no cut-off points are available that are style, gender or age specific, therefore, the link between the utilisation of field or laboratory testing with the aesthetic performance of dancers is not clear yet and demands further investigations. One study with contemporary female pre-professional and professional dancers (mean age 27 ± 5.9 years) found that a 6-week circuit and vibration training

were effective to improve both selected fitness components and aesthetic competence. More specifically, jump-height improved by 11%, upper body muscular endurance by 22%, aerobic fitness by 11% and aesthetic competence by 12% ($p < .05$) (Angioi et al., 2012). Similarly, Twitchett and colleagues found that pre-professional ballet dancers ($f = 14$, $m = 3$; mean \pm SD; $19 \pm .8$ years) showed positive artistic performance enhancement results after a 10-week exercise intervention for one hour per week. The intervention focus was on aerobic and muscular endurance. The intervention group showed significant differences in control ($p = .039$), skill ($p = .043$) and the “x-factor” ($p = .033$) (Twitchett et al., 2011). Even though the results are a positive indication that supplementary training away from the studio may provide positive results in dancing performance, their results need to be considered with their associated limitations in mind. Angioi and associates had a small mixed sample of dancers, therefore, it is not possible to generalise their results. Considering that there are no normative data on certain physiological parameters such as jump-height, and the large standard deviation the authors are reporting, it cannot be stated with certainty whether the mean difference that was observed is a sufficient improvement. Similarly, the Twitchett and colleagues study had a small sample of dancers of mixed genders. The authors reported the results of the aesthetic performance only but not any physiological adaptations. Both studies utilised video recordings to assess the performance of the dancers. The observation of the dancers through the screen may be adding even more subjectivity in the perception of the performance. In addition, a dancer may perform well one day and not another day, therefore, this type of assessment may need more trials so as to observe lasting change in performance.

Assessment of physiological parameters such as muscular strength and power has been used as a tool for talent identification in sport (Pienaar et al., 1998, Taylor et al., 2010), but not in dance. It has been argued that the utility of such assessment during one-off auditions may be questionable (Abbott and Collins, 2004), but they may be useful in relation to talent development (Walker et al., 2010) and potentially injury prevention (Allen et al., 2013, Bronner et al., 2018).

2.8 Injury Prevention in sport

The progressive increase in intensity of sport competition and training together with the early specialisation of youth sport, in recent years, results to both benefits and problems (Soomro et al., 2016). A benefit would be the opportunity youth gets to participate in organised training settings, develop self-esteem, socialisation, and general health (DiFiori et al., 2014). This participation, however, may come at a psychological (Côté and Hay, 2002) and physiological cost, through lack of physical preparation (Emery et al., 2005, Emery et al., 2007, Herman et al., 2012), overexposure (Kaleth and Mikesky, 2010, Myer et al., 2015a), overtraining (Gabbett et al., 2014), burnout (DiFiori et al., 2014), and an increased risk of injury (Franklin and Weiss, 2012, DiFiori, 2010b).

Sport and recreational activities have been identified as the leading cause of injury in youth (King et al., 1998, Emery et al., 2006, Kahl et al., 2007, Caine et al., 2008). The burden of sports injuries is among the major public health problems due to the socioeconomic effect on the individual and the society (De Loes, 1990, Caine et al., 2006a, Collard et al., 2011, Öztürk and Kılıç, 2013). For this reason, sports medicine has an important role in the cure and the

prevention of injuries (Öztürk and Kılıç, 2013). Close to three decades ago the World Health Organisation had set out a “health for all by the year 2000” policy and the European Council launched a European coordinated research project called “Sports For All: Sports Injuries and Their Prevention” with a remit to improve understanding of sports injuries and develop evidence-based prevention strategies. van Mechelen and colleagues developed a model called “sequence of prevention” that consisted four steps: (1) establishing the extend of the sports injury problem, (2) establishing the etiology and mechanism of sports injury, (3) introducing preventive measures and (4) assessing the effectiveness of these preventive measures by repeating step 1 (Van Mechelen et al., 1992). Due to a number of associated limitations of the four-stage model approach, such as the lack of description of the directions needed for research that lead to direct injury prevention, and the lack of implementation strategy, the Translating Research into Injury Prevention Practice (TRIPP) framework (Figure 2-3) for research leading the real-world sports injury prevention was developed (Finch, 2006).

The TRIPP framework is based on a series of steps that are necessary to build evidence for injury prevention. Stage-one is built around reliable injury surveillance in order to assess and establish the extend of the problem with clear and transparent methodology and definitions. Stage-two is based on understanding the aetiology of why injuries occur, with a multidisciplinary approach, as to what rehabilitation strategies could be effective and why.

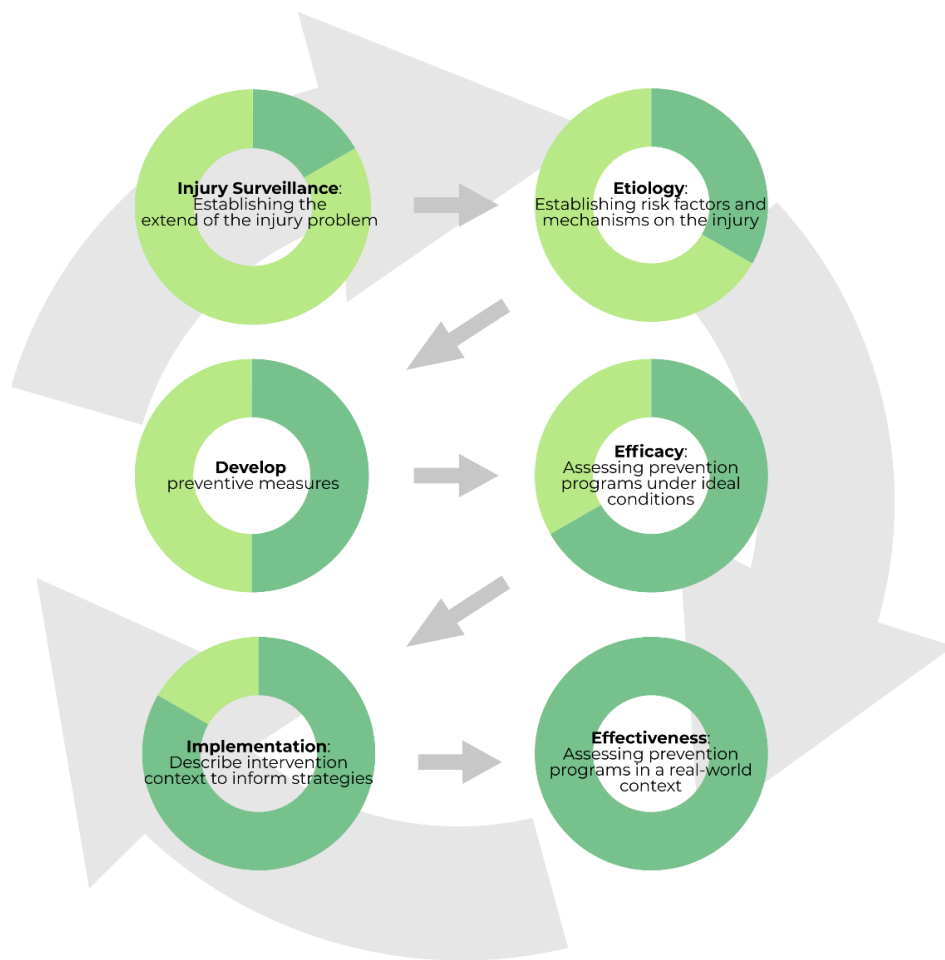


Figure 2-3. The Translating Research into Injury Prevention Practice (TRIPP) framework for research leading the real-world dance injury prevention (adopted from Finch, 2006).

Stage-three is about the identification of potential solutions to the injury problem and the development of appropriate preventative measures. Stage-four is based on the efficacy assessment of the intervention that could involve laboratory testing, focus groups, or small

group assessments. During this stage of the framework, important information such uptake or, or compliance with implemented interventions, reasons for use/non-use of the intervention that is being assessed, drop-out rates across both study arms that could potentially rule out any systematic bias related to the intervention and adverse effects of the intervention. Lastly, the final stage of the framework stage-six corresponds to both the implementation of the intervention in the real-world context and evaluation of its effectiveness (Finch, 2006). In the past decade, the International Olympic Committee (IOC) in collaboration with 11 research centres (IOC, 2019) across the world (Table 2-2) have developed several programmes that focus on the prevention of injuries and illnesses of elite and recreational athletes.

Table 2-2. International Olympic Committee Research Centres

The Australian Centre for Research into Injury in Sport and its Prevention (Edith Cowan University and La Trobe University Sport and Exercise Medicine Research Centre, Australia)
Sport Injury Prevention Research Centre (University of Calgary, Canada)
Institute of Sports Medicine & Sports Orthopedic Research Centre-Copenhagen (SORC-C) (Copenhagen University Hospital, Denmark)
French-speaking Research Network for Athlete Health Protection & Performance (French Institute of Sport; University and University Hospital of Liège; Luxembourg Institute of Research in Orthopedics, Sports Medicine and Science; National Sport Institute of Quebec; Geneva University Hospitals)
Yonsei Institute of Sports Science and Exercise Medicine (Yonsei University, Wonju Severance Christian Hospital, Korean Sports and Olympic, Sol Hospital, Korea National Sport University, Republic of Korea)
Amsterdam Collaboration on Health & Safety in Sports (VU University and Academic Medical Centre, Netherlands)
Oslo Sports Trauma Research Centre (Norwegian School of Sport Sciences, Norway)
Aspetar Orthopaedic and Sports Medicine Hospital (Qatar)
Sport, Exercise Medicine and Lifestyle Institute (University of Pretoria, University of Stellenbosch, South African Medical Research Council, South Africa)
London's Institute for Sports, Exercise and Health and National Centre for Sports Exercise and Medicine (United Kingdom)
United States Coalition for the Prevention of Illness and Injury in Sport (United States Olympic Committee, Steadman Philippon Research Institute, The University of Utah, USA)

Results from several injury prevention implementation studies reveal that the injury risk reduction can be as much as 50% (Engebretsen et al., 2014). Brunner and colleagues in their umbrella review on the effectiveness of lower extremity injury prevention programmes in team-sport athletes, further support that the utilisation of such programs can reduce injury

incidences/rates (Brunner et al., 2019). Lower extremity injuries are among the most common, accounting for over 60% of the overall injury burden in youth sport (Emery et al., 2015).

2.8.1 Injury prevention and strength training

Behringer and colleagues in a meta-analysis (42 studies, n= 1,728 participants) on the effectiveness of strength training for strength development in children and adolescents showed that resistance training is an effective and safe way to enhance muscle strength and motor skill performance (jumping, running, throwing) in children, adolescents (Behringer et al., 2011), and athletic performance (Suchomel et al., 2016) when it is appropriately prescribed and supervised. Resistance training is defined as exercise where the muscles are required to contract against resistance (e.g. bodyweight, elastic bands, barbells, dumbbells) (Behringer et al., 2010).

Lower extremity strength training has been shown to be as effective, or more effective than balance training for enhancement of balance and proprioception (Blackburn et al., 2000, Bruhn et al., 2004). Lephart and colleagues, in a randomised controlled trial on the effect of basic strength training versus a combination of plyometric training and basic strength training found that strength training alone was enough to improve the neuromuscular characteristics of the lower extremity in female athletes, suggesting that this could potentially reduce the risk of injury during a drop-landing (Lephart et al., 2005). It is important to mention, however, that the protocol they used was a local muscular endurance program as the repetitions were 20-30 per set. An earlier four-year prospective cohort study demonstrated changes in both the rate and type of injury incidence when a college soccer team employed a strength training regime in year three and four of the study. The researchers could not state with certainty that improved

strength was the reason of the injury decline, due to the unpredictability of the sport, players characteristics (skill level, fitness) and weather conditions, they did suggest that overuse injuries may be significantly reduced through strength training (Lehnhard et al., 1996). Athletes with higher levels of strength were at reduced risk of injury compared to lower strength levels athletes. In addition, when strength was regarded as an injury risk moderator, stronger athletes were able to tolerate the given workload better and at a reduced risk (Malone et al., 2018).

Herman and associates, in a randomised controlled laboratory study found that strength training alone is not enough to alter knee and hip kinematics and kinetics, therefore, may not be sufficient to reduce injuries in female recreational athletes. The researchers suggest that the effect of strength training on lower extremity biomechanics, should be investigated further in combination with other intervention methods (Herman et al., 2008). A systematic review (9 studies), on the risk factors for patellofemoral pain syndrome, the most commonly diagnosed condition in young athletes, however, revealed significantly lower knee extensor torques in the patellofemoral pain syndrome group than in the controls. The authors suggest that injury prevention programs with strength focus can lead to a reduction of this syndrome, which in most cases is a result of overuse or an increase of physical activity (Lankhorst et al., 2012). Moreover, Lauersen and colleagues in a meta-analysis (25 studies, n= 26,610) on the effect of physical activities on sports injuries showed that stretching had no beneficial effect whereas proprioception and strength training in multiple exposures showed increasing effect. The researchers suggest that injury prevention interventions could significantly reduce both acute and overuse injuries by almost 50% (Lauersen et al., 2014).

Strength training has been anecdotally, associated with increased muscle mass, loss of flexibility, loss of the aesthetic look of the dancer and therefore compromised performance (Koutedakis and Jamurtas, 2004, Koutedakis et al., 2005). Research, however, has shown no negative influence of the aesthetic appearance of the dancers who participate in physical conditioning training program (Koutedakis and Sharp, 2004, Mistiaen et al., 2012). Research on the relationship of muscular strength, components of strength and injuries in dance is based on cross-sectional design studies (Angioi et al., 2009, Twitchett et al., 2010, Koutedakis et al., 1997a, Koutedakis et al., 1997b, Gamboa et al., 2008). Therefore, the evidence on the preventative effect of strength in the injury incidence in dance is unclear and questionable due to low quality research (Moita et al., 2017).

2.8.2 Neuromuscular Control

Neuromuscular control, can be defined as the precise recruitment of muscle fibres in the appropriate muscle groups for the production of efficient and coordinated movement (Siff, 2003). Coordination in movement has been defined as the problem of mastering the redundant *degrees of freedom* of a particular movement (Turvey, 1990). Degrees of freedom, or independent elements, are the abundant action possibilities the human body has due to its anatomical structure (Coker, 2017). The inflow of proprioceptive information about the whole body creates synergies (Profeta and Turvey, 2018), between neurons, muscles, and joints (Heiderscheit et al., 2002), that allow the reduction of the functional degrees of freedom to a more controllable level (Heiderscheit et al., 2002).

Muscle synergies are coherent activations of a group of muscles in space or time (d'Avella et al., 2003).. Three aspects of synergies have been identified: 1) a group of elements that work together to achieve a common goal, 2) the same group of elements demonstrates flexible interactions in order to adapt to the ongoing environmental changes and stabilise the performance, and 3) the task-dependent organisation of these elements (Latash, 2008). Synergies are macro and micro relative concepts, as any given synergy is composed by other synergies (Kelso, 2000). During new motor tasks, there are no synergies to stabilise the performance, it is through practice that they get developed (Latash, 2012b), with vision and proprioception being of particular importance, both for the acquisition and the execution of skilled movement (Coker, 2017).

Proprioception refers to the afferent information provided from the proprioceptors, which are mechanoreceptors that are primarily found in capsules, ligaments, muscles and tendons (Riemann and Lephart, 2002a). The proprioceptors provide information about the body's position and movement through the detection of changes in joint position, muscle/tendon tension, and equilibrium (Coker, 2017). These receptors are classified into four groups. Type-I, typically found in the ankle ligaments, adapt slowly, have a low threshold and are continuously firing, even at rest. Type-II receptors are dynamic, have fast adaptation capacity and they too have low threshold. Type-I are thought to be giving postural sense to the central nervous system, whereas Type-II seem to be active at the beginning of the joint motion. Type-III are also dynamic, with slow adaptation capacity but have high threshold and are active at the extremes of movement (e.g. *en pointe* in ballet). Lastly, Type-IV are free nerve endings in

the tissues and are responsible for sensation or perception of pain (Michelson and Hutchins, 1995).

Joint receptors, which are characterised as Type-II, III or IV, vary in their location and their function. Ruffini-ending mechanoreceptors have the capacity to monitor joint position and displacement, angular speed, and intra-articular pressure (Johansson et al., 1991), whereas, Pacinian corpuscles appear to have the ability to detect joint acceleration (Bell et al., 1994). Golgi tendon organ-like endings are corpuscles with similar action to the Golgi tendon organs, but are located around the ligaments, and they are monitoring tension especially at the end range of the range of motion (Cardinale et al., 2011).

Two proprioceptors, both Type-I (Cardinale et al., 2011), that are important to athletic performance (e.g. jumping, running) are the Golgi tendon organs and the muscle spindles (Flanagan and Comyns, 2008). The Golgi tendon organs, are located in the myotendinous junction, provide information on tendon force and their main function is to act as a brake against excessive contractions (Utley and Astill, 2008), by inhibiting agonist muscles and facilitating antagonist muscles (Brooks et al., 1996). The muscle spindles are muscle length receptors and are located in most skeletal muscles but are more concentrated in muscles that exert fine motor control and large muscles which are rich in slow twitch fibers (Utley and Astill, 2008).

In sport and dance, training provides the environment for constant review, modification and refinement of motor control. Neuromuscular control depends on the correct and accurate functioning of the nervous system (Latash, 2012a, Fort-Vanmeerhaeghe et al., 2016). The

nervous system provides the signals that activate the muscles, and the muscles produce the necessary force (Cardinale et al., 2011). This complex system is subdivided in the central nervous system (CNS) and the peripheral nervous system (PNS). The PNS can be subdivided into a sensory or afferent division, which detects environmental changes, and the motor or efferent division, that transmits signals away from the CNS (Coker, 2017). The integration and analysis of the sensory input, efferent motor commands and resultant movements (Riemann and Lephart, 2002b), create interactions between segments of the body or joints. This interaction is often referred as coupling, and refers to the notion that the movement of one segment (or joint) can affect the motion of another segment (or joint) (Hamill et al., 2012). Coupling also refers to the relative timing, or synchrony between joints (McClay and Manal, 1997). Deviations from such motions are called “asynchronous” and are thought to have implications for injuries (Hamill et al., 2012).

Experts in the field of neuroscience suggest that the afferent system provides information that is utilised for planning actions but also for correcting ongoing movement in case of inaccuracies or changes in the environment (Riemann and Lephart, 2002b, Latash, 2012a). Other experts in the field, however, suggest that in explosive sports moves, the forces are too fast for this system to process (Bosch, 2015). As such it has been hypothesized that the reactive rapid control is generated by the efferent feedforward system, through co-contractions of agonists and antagonists muscles, facilitating the correct amount of stiffness around the joint (Bosch, 2015). More specifically, an investigation of ankle inversion injuries through a computer simulation model has shown that an ankle injury occurs within 62 milliseconds (DeMers et al., 2017). Reflexes at approximately 80 milliseconds fail to fully prevent excessive inversion,

whereas, moderate to high levels of coactivation, also known as reflexes, are able to correct perturbations in movement within 60 milliseconds (Loeb et al., 1999).

Lee and associates in their investigation on the biomechanics and muscle activation in injured ballet dancers during a jump-land task with turnout (*Sissone Fermée*) revealed that dancers who had sustained an ankle injury had insufficient activation from the foot and hip muscles. The injured dancers required more muscle effort for ankle stability control, and they used a “load avoidance strategy” to avoid re-injury. The authors suggest that neuromuscular training for ballet dancers is necessary for injury prevention (Lee et al., 2012).

It is suggested that through training, neuromuscular control can be improved (Fort-Vanmeerhaeghe et al., 2016). It has been hypothesised that the development of correct movement efficiency patterns is essential for the safe loading of an injured or deficient body region, by minimising the risk of injury or the creation of compensatory movement patterns (Allen et al., 2013).

2.8.3 Neuromuscular Training

Neuromuscular training is generally described as the use of multi-intervention training programs with a combination of balance and proprioception, resistance training, agility (Emery et al., 2015) plyometric, together with sports specific exercises (Grindstaff et al., 2006, Hübscher et al., 2010). Although there is no consensus to suggest an optimal neuromuscular program (Fort-Vanmeerhaeghe et al., 2016), neuromuscular training programs have shown to be effective in decreasing associated risk factors for injury (Wilkerson et al., 2004, Chimera et al., 2004, Lephart et al., 2005, Hewett et al., 2005, Myer et al., 2005, Myer et al., 2006) and

injury rates (Caraffa et al., 1996, Hewett et al., 1999, Heidt et al., 2000, Myklebust et al., 2003, Olsen et al., 2005, Mandelbaum et al., 2005, Waldén et al., 2012). DiFiori and associates, in a recent position statement from the American Medical Society for Sports Medicine on overuse injuries and burnout in youth suggest that strength training and pre-practice neuromuscular training can reduce and prevent injuries in youth and particularly lower extremity injuries (DiFiori et al., 2014).

A recent meta-analysis of meta-analyses (8 studies, $n \approx 74,624$ participants) of anterior cruciate ligament (ACL) injury prevention interventions that included neuromuscular training, showed that the risk of all ACL injuries was reduced by an overall 50% [OR=0.5 (0.41 – 0.59); $I^2=15\%$] and a 67% reduction [OR= 0.33 (0.27 – 0.41); $I^2=15\%$] in females (Webster and Hewett, 2018). Even though one included meta-analysis found an 85% reduction in relative risk for males (Sadoghi et al., 2012), and a large study on male athletes (675 intervention, 850 control) found a 77% reduction in the risk of ACL injuries in (Hübscher et al., 2010), the authors report that there is limited information to make conclusions for male athletes (Webster and Hewett, 2018). Emery and colleagues in another systematic review and meta-analysis (25 studies) demonstrate a substantial overall protective effect of neuromuscular injury prevention training programmes in youth team sport (<19 years old) for the reduction of lower extremity injuries. The authors reported the incidence rate ratios (IRR) for eight studies that had a lower extremity injury outcome (IRR= 0.64, 95% CI 0.49 to 0.84), and five studies that had knee injuries as primary outcome (IRR= 0.74, 95% CI 0.51 to 1.07) (Emery et al., 2015). Myer and associates suggest that there is an age-related association between the implementation of neuromuscular training programs and ACL injuries. The authors recommended the implementation of such

programs during early adolescence before the onset of neuromuscular deficits (Myer et al., 2013b). In an earlier study Myer and colleagues suggest that training protocols will have better compliance from the athletes, if they included evidence-based injury prevention exercises but are designed with the focus of performance enhancement (Myer et al., 2004).

It has been demonstrated that neuromuscular training is also effective for performance improvement together with the prophylactic effect against injury risks during sports activities in children (Rössler et al., 2016a, Rössler et al., 2017) and youth (Zemková and Hamar, 2018). Reis and colleagues conducted a randomised trial, with a small sample of young footballers (n= 36), to investigate the effect of a neuromuscular training program called “FIFA 11+” against usual warm-up and found that the intervention group in all physiological parameters. In detail, the intervention group improved in the hamstring, quadriceps ratio (H:Q_{ratio}) by 1.8 to 8.5% (p <0.05), squat jump (13.8%), countermovement jump (9.9%), 5 and 30 meters sprints (8.9% and 3.3% respectively), agility (4.7%), slalom (4.8%) and balance (30%) performances (Reis et al., 2013).

The FIFA 11+ is a neuromuscular workout that lasts approximately 20-30 minutes, consisting of 15 exercises. It was developed by the Federation Internationale de Football Association (FIFA) Medical Assessment and Research Centre. It consists of dynamic exercises selected for injury prevention based on scientific evidence and best practice (Bizzini et al., 2013). The exercises are grouped into three parts, parts 1 and 3 include running exercises combined with active stretching, controlled partner contacts, planting and cutting movements, whereas Part 2 incorporates strength, agility and balance conditioning exercises (Junge et al., 2011).

Randomised trials have demonstrated the effect of FIFA 11+ on the reduction of training injuries (37%), on match injuries (29%) and severe injuries (50%) (Soligard et al., 2008), isokinetic strength and muscle balance for the H:Q ratio (Brito et al., 2010, Daneshjoo et al., 2012b) and proprioception, static and dynamic balance (Daneshjoo et al., 2012a).

Yoo and colleagues in a meta-analysis (7 studies, n= 10,618 participants) on the effectiveness of neuromuscular training on the prevention of ACL injuries in female athletes suggest that strength and plyometric exercises were essential components of such training protocols, but balance exercises were not. Their focus, however, was on adolescent female soccer and handball players (Yoo et al., 2010). Generally, research suggests that the exclusion of balance training diminishes the prophylactic effect of neuromuscular injury prevention training (Pfeiffer et al., 2006, Collard et al., 2010).

Low compliance (<20 sessions) has also been identified as a factor for lack of preventive effect of neuromuscular training against injuries (Steffen et al., 2008). Sugimoto and associates in a meta-analysis (6 studies, n= 5,231 participants), investigating the dosage effect of neuromuscular training on the reduction of ACL injuries in female athletes, found that participants in low compliance studies demonstrated a 4.9 times greater relative risk of ACL injury than participants in high compliance studies (IRR= 0.18, 95% CI 0.02 to 0.77 (Sugimoto et al., 2012). Even though there is some evidence of adaptations from sub-maximal exercise as early as three weeks (Vila-Chã et al., 2010), one study has shown that it takes longer for neural adaptations to occur in the trunk and the lower extremities (>6 weeks) rather than the upper extremities (Chilibeck et al., 1997). Sugimoto and colleagues suggest that adaptations from

neuromuscular training take a certain amount of time (Sugimoto et al., 2012). Faude and colleagues reported that the effect size in the training adaptations was higher in balance/stability ($d= 0.67$, 95% CI 0.33, 1.01), leg power ($d= 0.35$, 95% CI 0.10, 0.59), sprint abilities ($d= 1.16$, 95% CI 0.72, 1.59), and sport-specific tests ($d= 1.15$, 95% CI 0.49, 1.81) when the FIFA 11+ injury prevention intervention was performed more than 23 training sessions (Faude et al., 2017). Moreover, Steib and colleagues conducted a meta-analysis (16 studies, $n \approx 20,590$ participants) on the dose-response relationship of neuromuscular training for injury prevention in youth athletes. Results from 16 included trials indicate an overall risk reduction of 42% with neuromuscular training (IRR= 0.58, 95% CI 0.47, 0.72). They also found that the largest risk reduction was observed when the training frequency was two (IRR= 0.50, 95% CI 0.29, 0.86) or three times (IRR= 0.40, 95% CI 0.31, 0.53) per week. The authors concluded, keeping in mind the limited number of studies and the methodological flaws of the included studies, that short bouts of 10-15 minutes with a total weekly training volume of 30-60 minutes within 20-60 sessions that lasted up to six months had the largest preventative effect (Steib et al., 2017).

Most of the studies on injury prevention focus on acute injuries and particularly ACL injuries (Caraffa et al., 1996, Hewett et al., 1999, Heidt et al., 2000, Myklebust et al., 2003, Olsen et al., 2005, Mandelbaum et al., 2005). LaBella and colleagues, however, in a clustered RCT with a large sample ($n= 1492$) observed that the intervention group had a 56% and 66% decrease in acute noncontact injuries and noncontact ankle sprains respectively, as well as a 65% decrease in gradual onset injuries (LaBella et al., 2011). This is also supported from another large ($n= 1837$) cluster RCT by Olsen and associates who reported an incidence difference between the

intervention and the control group in both acute (rate ratio 0.51, 95% CI 0.39, 0.56) and overuse injuries (rate ratio 0.43, 95% CI 0.25, 0.75) (Olsen et al., 2005).

2.9 Injury prevention in dance

Compared with the high quality and volume of research published on youth sports (Emery et al., 2015, Soomro et al., 2016, Faude et al., 2017, Steib et al., 2017, Brunner et al., 2019), youth male and female athletes (Sugimoto et al., 2014b, Al Attar et al., 2016) in soccer (Silvers-Graneli et al., 2015, Zarei et al., 2018, Arundale et al., 2018), rugby (Hislop et al., 2016, Hislop et al., 2017), basketball (Emery et al., 2007, LaBella et al., 2011), handball (Wedderkopp et al., 2003, Olsen et al., 2005), limited research exists on injury prevention in dance. An epidemiological review of injuries in pre-professional ballet dancers identified only two injury prevention studies in ballet (Caine et al., 2015), both of which were conducted with psychological interventions. Noh and colleagues (2007) suggest that interventions that enhanced coping skills or reduced stress were associated with reduced time spent injured (Noh et al., 2007). Kaufman and associates (1996), in a two-year non-randomised intervention were they investigated if education in the form of counselling could reduce the incidence of reproductive dysfunction and injury, found no significant difference between the participants who completed the intervention and those who dropped out of the study (Kaufman et al., 1996).

Research on injury prevention in other styles of dance is also scarce. The literature review indicated two experimental studies that investigated the effect of physical conditioning on

musculoskeletal injuries in pre-professional university dancers (Mistiaen et al., 2012, Roussel et al., 2014). Mistiaen and colleagues, conducted a six-month non-randomised trial with university students (n= 41), however because it was a sample of convenience they did not include a control group in their sample, therefore their results cannot determine whether there is an effect or not on injury incidence (Mistiaen et al., 2012). Roussel and associates, conducted a four-month randomised trial with university students (n= 44) and found no differences in physiological parameters or injury incidence between the two groups, except for injuries in the lower back with the conditioning group having significantly less ($p = .019$). Four months of physical conditioning, with a potential of total training sessions of 24, can induce physiological adaptations in explosive strength performance (Lesinski et al., 2016, Otero-Esquina et al., 2017), and in particular standing broad jump (Argus et al., 2012) in athletes, if the training program is designed correctly and the load is appropriate to the individual. The researchers reported no differences between the conditioning group and the health promotion program group, therefore, the exercises, their progression, and the load prescription may be important confounding factors of their results. In addition, the researchers in both studies have not reported the training protocol they used; therefore, their studies cannot be replicated. Another methodological concern was the fact that the injuries were self-reported introducing recall bias from the participants. Finally, both studies were conducted with pre-professional university students who did not specialise in one style of dance, therefore, their results cannot be generalised to vocational adolescent pre-professional or professional dancers.

The state of knowledge is based on a small number of studies with low methodological quality, therefore, the evidence on the preventative role of strength in dance injuries remains unclear.

This makes the design of potential injury prevention interventions difficult (Moita et al., 2017). Yau and colleagues, however, in a retrospective analysis of data of potential predictors of injury in pre-professional ballet and contemporary dancers, identified differences between styles and gender in traumatic injuries, but no differences were observed between gender or style of dance in overuse injuries. The researchers suggest that strategies for the prevention of traumatic injuries should be both style and gender specific, whereas for overuse injury prevention, strategies can be generic and not gender specific (Yau et al., 2017), however, the limitations of the study design (i.e. retrospective analysis of data), injury rate calculation (i.e. 1000 person-days) and potential bias of the dance program being more ballet focused in high school but contemporary dance in college, need to be taken under consideration when interpreting aforementioned observations.

The cost of dance related injuries in a professional company has been compared with that of a college athletic department or a professional sport team (Garrick and Requa, 1993). The high prevalence of injuries demonstrates the importance of both specialised medical teams but also the implementation of injury prevention strategies in ballet (Sobrino et al., 2015). It has been demonstrated that a comprehensive injury audit program together with a proactive exercise prescription program can reduce injury incidence and severity in professional contemporary (Bronner et al., 2018) and ballet (Allen et al., 2013) dancers. Moreover, LaBella and colleagues conducted a cost-effectiveness analysis of their injury prevention intervention and found that in order to avoid one injury that needed surgery, the coach-led intervention would have to be applied on 189 athletes. This meant that 16 basketball or 11 football coaches would need to be trained on the intervention, which equates to approximately \$1280, a cost that is substantially

less than one surgical operation (LaBella et al., 2011). Moreover, recent evidence indicates that injury prevention programmes have reduced the economic burden of soccer injuries by over \$2.7 million (Marshall et al., 2016). Considering the lack of research on injury prevention interventions in dance (Caine et al., 2015), the benefits of investigating the effect of an injury prevention intervention in adolescent pre- professional dancers are of vital importance.

3 Growth, maturation, and overuse injuries in aesthetic sports: A Systematic Review

Parts of this chapter have been accepted for publication at the Journal of Dance Medicine and Science.

The author of the Thesis appears as the leading author.

The purpose of this systematic review had as a primary aim to investigate the relationship between growth and maturation with overuse injuries in aesthetic sport/activities.

3.1 Introduction

Aesthetic sports are disciplines where performance is partly or mainly evaluated on the basis of criteria like “artistry” and “style” (Tännsjö and Tamburrini, 2000) with recent studies accepting these are: dance (e.g. ballet, modern), figure-skating, gymnastics, rhythmic-gymnastics, diving and synchronised swimming (Krentz and Warschburger, 2011). Training for these sports or activities may start as early as five or eight years old in ballet, gymnastics and synchronized-swimming, respectively (Starkes et al., 1996). It is accepted that elite performance in these disciplines relies on early-specialisation training (Malina, 2010), defined as sport or disciplines based on the following three criteria: a) participation in intensive training and/or competition greater than eight months per year, b) exclusion from participation in other sports, and c) involving children around the age of 12 (LaPrade et al., 2016).

Early specialisation training is intensified during adolescence, i.e. ages between 10 and 19 years old (Malina, 2010). During this period adolescents go through accelerated growth and maturation (Engebretsen et al., 2010). Growth refers to changes that can be quantified, either in the size of the body or the size of specific body regions, while maturation, refers to both

functional and structural qualitative changes in the system of the body's progress towards a mature state (Beunen and Malina, 2005). Epidemiological studies (Caine et al., 1989), systematic (Kox et al., 2015b) and narrative reviews (Feeley et al., 2015, Caine et al., 2014, Maffulli et al., 2011a) indicate that during this period of accelerated growth, adolescent athletes are more susceptible to overuse injuries.

An overuse injury is microtraumatic damage to tissues (e.g. bone, muscle, tendon) due to repetitive submaximal loading without sufficient time to heal or undergo the natural reparative process (Brenner et al., 2007). Associated risk factors for an overuse injury have been identified as growth factors (e.g. growth-spurt) intrinsic factors (e.g. previous injury, menstrual dysfunction) and extrinsic factors (e.g. training load or technique) (Maffulli et al., 2011b). Training or external load is any sport related work completed by the athlete over varying periods (from seconds to years) with varying magnitude (duration, frequency and intensity) and is measured independently of their individual characteristics (i.e. level of fitness) . However, the lack of uniform definitions on injury and illness prevalence in all aesthetic sports (Mountjoy et al., 2015), or training load, together with the fact that literature reporting overuse injuries depends on recall, self-reported data and are retrospectively collected, can make their reliability and comparability questionable. Moreover, the lack of data on children and adolescents makes it difficult to determine the causal relationship between overuse injuries growth and maturation (DiFiori, 2010a).

Despite the high incidence of overuse injuries in adolescents in sport (DiFiori et al., 2014, Kox et al., 2015b), such injuries are underestimated (45.9% to 54%) over acute injuries mainly

because most epidemiological studies define injury as time loss from participation (DiFiori et al., 2014). In aesthetic sports/activities, overuse injuries have higher prevalence than acute injuries. More specifically, these are 64.4% in gymnastics (Caine et al., 1989), 44.1% in figure skating (Dubravcic-Simunjak et al., 2003), and 72% in pre-professional dancers (Ekegren et al., 2014). A number of mechanisms are hypothesised on the reason behind the increased injury occurrence in adolescents. During this period of accelerated growth, there are changes to limb length, limb mass and moments of inertia (Adirim and Cheng, 2003, Hawkins and Metheny, 2001). These changes may cause delays or regressions in specific motor control aspects such as neuromuscular control, postural stability and intersegmental/interlimb coordination (Quatman-Yates et al., 2012). In addition, maturity timing or status, or the combination of both may affect interlimb asymmetry and neuromuscular control that could potentially lead to increased likelihood of injury (Read et al., 2018b). Evidence of the relationship of injuries with growth and maturation in aesthetic sport or activities is either equivocal or not well-established (Steinberg et al., 2014b). This complex biological process varies vastly in adolescents, therefore, a better understanding is warranted in order to be able to minimise the risk of injuries at a young age as they increase the risk of reinjury at a later stage (Caine et al., 1989, DiFiori, 2010a). The aim of this systematic review, therefore, was to investigate the association between growth and maturation with overuse injuries. The review focused on one indicator of growth, stature and on two indicators of maturation, skeletal and chronological age, and menarche. The secondary aim was to explore whether training load was associated with growth, maturation in the prevalence of overuse injuries in aesthetic sports or activities.

3.2 Methods

3.2.1 Search methods for identification of articles

Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2015) four electronic databases, EMBASE, PubMed, CINAHL, and Sport Discus were searched up until 19 August 2018 to identify potentially relevant articles. Table 1 depicts the combination of Medical Subject Headings (MeSHs) and text words used in our search. Two investigators (NK and PCD) independently conducted two identical searching actions in the aforementioned databases. The search strategy was adapted from the American Medical Society for Sports Medicine position statement on overuse injuries and burnout in youth sports (DiFiori et al., 2014). The concepts around sports/athletics were, therefore, adapted in order for the search algorithm to be appropriate for aesthetic sports (see Table 3-1).

3.2.2 Eligibility criteria for considering articles for the review

Studies that measured and/or investigated the relationship/effects between growth, maturation and injuries were included. Participants had to be involved in aesthetic sports/activities, either recreationally or professionally. In addition, we included studies where the effects and/or associations of growth and maturation with overuse injuries could be separated for the target population. Studies that just reported the prevalence of injuries without investigating associations or effects between growth, maturation and injuries in adolescents were excluded. The search strategy was not limited by language.

3.2.3 Selection of studies

Two authors (NK and PCD) independently screened and assessed the identified articles for eligibility. Potentially relevant studies were merged from each database and duplicates were removed. The articles were screened by title and by abstract and 196 articles were retrieved and screened for eligibility. Disagreements on study eligibility were resolved through consensus between NK and PCD or, when necessary, there was a meeting with a third author not involved in the assessment (MW). Full-text copies of all potentially relevant studies were retrieved and reviewed.

Table 3-1. Database search methodology

EMBASE strategy:

(sport* or dance* or ballet or gymnast* or rhythmic w2 gymnast* or artistic w2 gymnast* or vault or still w2 rings or horizontal w2 bar or balance w2 beam or pommel w2 horse or uneven w2 bars or ice w2 skat* or figure w2 skat* or synchronized w2 swim* or aesthetic w2 sport* or aesthetic w2 athlete).ab. AND (cumulative w3 trauma disorder* or athletic w2 injur* or injur* or trauma or adverse w2 effect* or adverse w2 event* or overuse).ab. AND (youth or adolescent or adolescence).ab. AND (matur* or maturity w2 status or maturity w2 timing or skeletal w2 age or peak w3 height velocity or growth w2 spurt or growth w2 tempo or growth w2 velocity or menarche).ab.

PubMed strategy:

((((((((((((((((((((((sports[MeSH Terms]) OR sport*[Text Word]) OR dance[Text Word]) OR ballet[Text Word]) OR gymnastics[MeSH Terms]) OR gymnast*[Text Word]) OR artistic w2 gymnast*[Text Word]) OR rhythmic w2 gymnast*[Text Word]) OR vault[Text Word]) OR still w2 rings[Text Word]) OR horizontal w2 bar[Text Word]) OR balance w2 beam[Text Word]) OR pommel w2 horse[Text Word]) OR uneven w2 bars[Text Word]) OR ice skating[MeSH Terms]) OR ice w2 skat*[Text Word]) OR figure w2 skat*[Text Word]) OR synchronized w2 swim*[Text Word]) OR aesthetic w2 sport*[Text Word]) OR aesthetic w2 athlete*[Text Word])) AND (((((((((((cumulative trauma disorders[MeSH Terms]) OR athletic injuries[MeSH Terms]) OR injur*[Text Word]) OR trauma[Text Word]) OR adverse effects[MeSH Terms]) OR adverse w2 effect*[Text Word]) OR adverse w2 event*[Text Word]) OR overuse injuries[MeSH Terms]) OR overuse[Text Word])) AND (((((((youth[MeSH Terms]) OR youth[Text Word]) OR adolescent[MeSH Terms]) OR adolescence[MeSH Terms]) OR adolescen*[Text Word])) AND (((((((matur*[Text Word]) OR maturity w2 status[Text Word]) OR maturity w2 timing[Text Word]) OR skeletal w2 age[Text Word]) OR peak w3 height velocity[Text Word]) OR growth w2 spurt[Text Word]) OR growth w2 tempo[Text Word]) OR growth w2 velocity[Text Word]) OR menarche[MeSH Terms]) NOT ((animal[MeSH Terms] NOT human[MeSH Terms])))

SPORTDiscus strategy:

((((Sport*) OR (danc*) OR (ballet) OR (gymnastic*) OR ((artistic w2 gymnastic* OR rhythmic w2 gymnastic* OR vault OR still w2 rings OR horizontal w2 bar OR balance w2 beam "or" "or" pommel w2 horse OR uneven w2 bars)) OR ((ice w2 skat* OR figure w2 skat*)) OR (synchronised w2 swim*) OR (aesthetic w2 sport*)) AND ((cumulative trauma disorders) OR (injur*) OR (trauma) OR (adverse w2 effect* OR adverse w2 event*) OR (overuse injuries) OR (overuse)) AND ((youth) OR (adolescent*) OR (adolescence)) AND ((matur*) OR (skeletal w2 age) OR (peak w3 height velocity) OR (growth w2 spurt) OR (growth w2 tempo) OR (growth w2 velocity) OR (menarche)))

CINHAL strategy:

Sport* OR danc* OR ballet OR gymnastic* OR ((artistic w2 gymnastic* or rhythmic w2 gymnastic* or vault or still w2 rings or horizontal w2 bar or balance w2 beam or pommel w2 horse or uneven w2 bars)) OR ((ice w2 skat* or figure w2 skat*)) OR synchronised w2 swim* OR aesthetic w2 sport* AND cumulative trauma disorders OR injur* OR trauma OR (adverse w2 effect* OR adverse w2 event*) OR overuse injuries OR overuse AND youth OR adolescent* OR adolescence AND matur* OR skeletal w2 age OR peak w3 height velocity OR growth w2 spurt OR growth w2 tempo OR growth w2 velocity OR menarche

3.2.4 Data extraction

Two authors (NK and PCD) independently extracted data using a pre-determined data extraction form (Table 3-2). Characteristics of studies extracted included study design, sport/activity, method of assessment, primary and secondary outcomes. Disagreement was resolved by discussion, followed if necessary, by scrutiny from a third author (MW). The primary outcomes were extracted according to the relationship between growth, biological

maturation, maturity status and timing, with overuse injuries including stress fractures but excluding acute injuries. Two biological maturation markers that are commonly assessed are the skeletal age (SA) and the secondary sex characteristics (Bergeron et al., 2015a). Both represent the chronological age (CA) of an individual when a specific level of maturity (status) of the hand-wrist bones, or the genitals was reached. Skeletal age is always relative to CA as it has limited utility as an individual value. The CA when specific maturation events take place correspond to maturity timing, which is commonly assessed by age at peak height velocity (PHV) and age at menarche (Bergeron et al., 2015a). The secondary outcomes were extracted based on the relationship between training load (hours per week, months per year) and overuse injuries.

3.2.5 Risk of bias assessment

Two researchers (NK and PCD) both independently and in duplicate assessed the risk of bias of the included publications. Disagreement was resolved by discussion followed if necessary, by scrutiny from a third author experienced in conducting systematic reviews (GSM). The assessment of the quality of reporting was not implemented, as there is evidence that such appraisals can create a misleading score and results. The use of quality scales and summarised scores can be problematic, as a biased but well reported study can receive credit, whereas, a well conducted study but poorly reported will be misclassified (Jüni et al., 1999). For this assessment, the Research Triangle Institute item bank (RTI-IB) was utilised. This recently revised tool covers observational study designs and comes with guidelines for the appropriate use and scoring (Viswanathan et al., 2013). As recently reported a study with one or more of the key items being rated negative or unclear was rated as of high risk of bias. The risk of bias

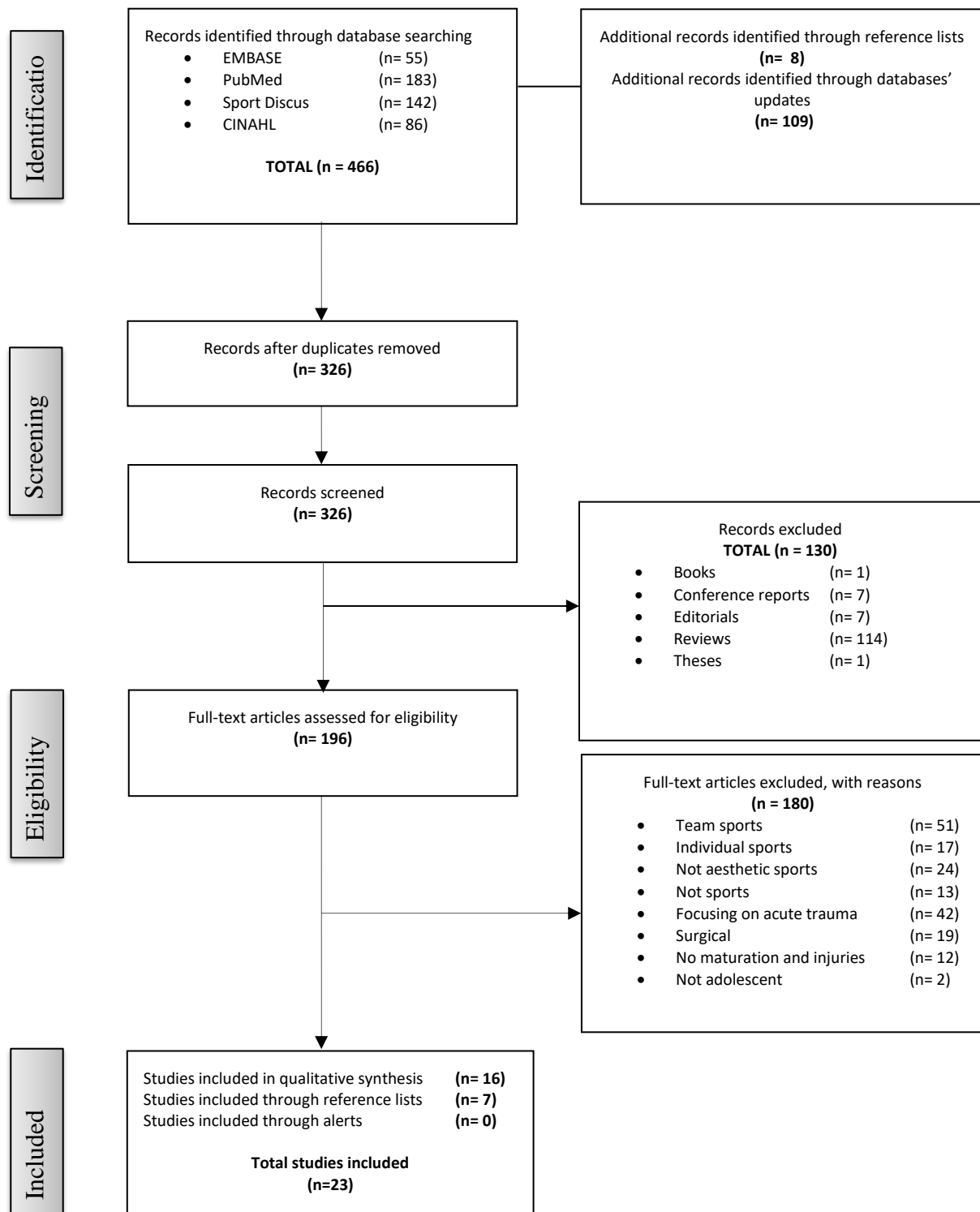
assessment was then based on the creation of a threshold in relation to the context of this review, as per RTI-IB guidelines (Viswanathan et al., 2013). Given that odds ratio and relative risk should be reported in observational studies in order to minimise outcome reporting bias, we completed the assessment having taken the latter into consideration.

3.3 Results

3.3.1 Included studies

A total of 466 potentially relevant articles were identified from the primary search. The articles were screened based on the title and abstract. After the duplicates were removed, 326 articles were screened for eligibility, leaving 16 eligible studies. The references of these 16 articles were checked in order to identify any more relevant publications; seven new articles were identified (total articles included, n=23). We requested unreported data from one author but there was no response (Kadel, 1992). The searching outcome and process is presented in the PRISMA flow diagram in Figure 3-1.

Figure 3-1. PRISMA flow diagram of the search process



3.3.2 Design

The design of the included studies along with sample size, mean age and assessments appear in Table 3-2. All studies were published between 1986 and 2014 and study locations included USA, Europe, China and Australia. No randomised controlled trials addressing the effect of growth and maturation on overuse injuries in aesthetic sports were available. This review (n=23) therefore was based on observational studies. Seven of the studies (7/23) were cohort,(Baranto et al., 2006, Bowerman et al., 2014b, Caine et al., 1989, Steinberg et al., 2014a, Carter et al., 1988, Chang et al., 1995, Kolt and Kirkby, 1999) five case-series (5/23),(Loud et al., 2005, Steinberg et al., 2011a, Carter and Aldridge, 1988, Micheli and Fehlandt, 1992, Maffulli et al., 1992) two case-control (2/23),(Lindholm et al., 1994, Warren et al., 1991) and nine cross-sectional studies (9/23).(Amaral et al., 2012, De Smet et al., 1994, Purnell et al., 2010, Steinberg et al., 2013, Thein-Nissenbaum et al., 2012, Warren et al., 1986, Goldstein et al., 1991, Kadel, 1992, Steinberg et al., 2011b)

Table 3-2. Summary of included studies

First Author, Year of publication, Country	Level of performance	Sport or Discipline	Gender, Sample Size	Mean Age	Study Design/Length	Assessment	Primary Outcome	Secondary Outcome
(Amaral et al., 2012); Portugal	National-International	Gymnastics	Female n=33	11.1±2.1	Cross-sectional	X-Rays, Skeletal maturation: Tanner Whitehouse TW3 method, Training data: interviews	Association between Ulnar Variance and skeletal age was noted (r=0.38; p<0.05)	n/a
(Caine et al., 1989); USA	Elite	Gymnastics	Female n=50	12.6	Cohort-prospective/ 1 year	Musculoskeletal screening, maturity assessment: Tanner's stages, injury surveillance	Association of competitive level (P<0.05) and maturation rate (P<0.06) in determining high or low injury risk.	n/a
(Carter and Aldridge, 1988); United Kingdom	Mixed level	Gymnastics	Female n=4 Male n=17	13.8	Case series/ 4 years	Skeletal maturation: X-Rays	Association of injuries with skeletal age	n/a
(Carter et al., 1988); USA	Competitive	Gymnastics	Male n=8	14.1	Cohort/ 27 months	Injury prevalence: questionnaire and X-rays	Association of chronological age and overuse injuries	n/a
(Chang et al., 1995); China	Elite	Gymnastics	<i>Study group:</i> Females (n=143), Males (n=118); <i>Control group:</i> Females (n=44), Males (n=19)	<i>Study group:</i> 14.4±2.4 <i>Control Group:</i> 13.9±1.4	Case control	Injury prevalence: questionnaire and X-rays	Association of repetitive stress in the wrists of adolescent gymnasts and localized growth disturbance of the distal-radius.	n/a
(Goldstein et al., 1991); USA	Pre-elite, Elite, National	Gymnastics Swimming	n=52	<i>Pre-elite</i> 11.8±1.1, <i>Elite</i> 16.6±1.6, <i>National</i> 25.7±3.5-: <i>AA/AAA</i> 14.6±2, <i>National</i> 18.6±1.6	Cross sectional-epidemiologic investigation	Demographic and training load data: interview, Injury prevalence: MRI	n/a	Association of chronological age and training hours per week with higher % of positive MRI results. Predictive value of 83.3% for MRI+ gymnasts and 73.3% for MRI- gymnasts
(Kolt and Kirkby, 1999); Australia	Elite, sub-elite	Gymnastics	Female n=64	12.6±1.7	Cohort/18 months	Injury prevalence & training load: self- reported log.	n/a	Growth plate injuries associated with loading (hours per week).

Table 3-2. (cont.) Summary of included studies

First Author, Year of publication, Country	Level of performance,	Sport or Discipline	Gender, Sample Size	Mean Age	Study Design/Length	Assessment	Primary Outcome	Secondary Outcome
(Lindholm et al., 1994); Sweden	Elite, sub-elite	Gymnastics	<i>Study group:</i> Female (n=22) <i>Control group:</i> Female (n=22)	<i>Study group:</i> Mean age= 15±0.8 <i>Control group:</i> Mean age=15±0.7	Case Control- prospective/ 5 years	Anthropometric data, hormonal analysis: immune-metric methods, maturation stage: Tanner's stages	Association of injury occurrence with hard training combined with late menarche compared with the control group (p<0.05)	n/a
(Maffulli et al., 1992); England	Club to international gymnasts	Gymnastics	Females (n=6), Males (n=6)	13.5	Case Series- prospective/ 11 years	Injury prevalence through X-rays	Association of chronic stress and skeletal immaturity with high incidence of osteochondritic lesions, intraarticular loose bodies	n/a
(Purnell et al., 2010) ; Australia	Mixed level	Gymnastics	Females (n=69) Males (n=4)		Cross-sectional- retrospective	Survey	A moderate correlation between increased chronological age and occurrence of chronic injury (r=0.561)	Chronological age and loading (hours per week) were a risk factor for injuries.
(De Smet et al., 1994); Unspecified-	Elite	Gymnastics	n=201	15.9	Cross-sectional	Anthropometric survey and X-rays	No association of ulnar variance and carpal angle with chronological age (p value not reported)	The impact load and compression may be more important than repetition (estimated by hours of training and years of gymnast activity).
(Bowerman et al., 2014b); Australia	Elite	Dance	Females (n=30), Males (n=16)	16±1.58	Cohort- prospective/ 6 months	Maturation assessment: Tanner stages, Skeletal maturation assessment: foot length, Alignment assessment: 2D video analysis	Growth is associated with a small to moderate increase in risk of lumbar and lower extremity overuse injury (RR= 1.41, CI= 0.93-2.13).	n/a
(Steinberg et al., 2011b); Israel	Recreational	Dance	Female (n=1336)	13.3	Cross-sectional	Injury prevalence: interviews, X-rays, MRI	Association of injury, re- injury and chronological age and growth spurt (P<0.001). The prevalence of injured girls increased significantly (P<0.001) from the age 8 to age 16	n/a

Table 3-2. (cont.) Summary of included studies

First Author, Year of publication, Country	Level of performance,	Sport or Discipline	Gender, Sample Size	Mean Age	Study Design/ Length	Assessment	Primary Outcome	Secondary Outcome
(Steinberg et al., 2013); Israel	Recreational	Dance	Female (n=569)	Mean Range age=8-16	Cross-sectional (Descriptive epidemiology study)	Questionnaires for participation, Self-reported injuries, interview for females, anthropometric data	Chronological age and age at menarche associated with injuries (p value not reported)	n/a
(Warren et al., 1991); USA	Professional	Dance	Female (n=98) Control group: (n=47)	21.87±4.5 (range 13-29)	Case Control	Interviews, anthropometric, venous sample, bone density scans	Association between age at menarche and stress fractures (r=0.28, P<0.004).	n/a
(Warren et al., 1986); USA	Professional	Dance	Female (n=75)	24.3	Cross-sectional	Survey	Correlation between stress fracture and age at menarche r= 0.4, p<0.01	n/a
(Kadel, 1992); USA	Professional	Dance	Female (n=54)	20.2±4.4	Cross-sectional	Injury prevalence & age at menarche: Survey	No correlation between chronological age and incidence of stress fracture, no association between age at menarche and stress fracture (P value not reported).	Dancers who had prolonged amenorrhoeic intervals (>6months), (F5.3, 1644=93, P= 0.002) and danced >5 hrs per day (F1.7, 150= 16, P= 0.015) were significantly more likely to have a stress fracture than those dancing <5 hrs per week.

Table 3-2. (cont.) Summary of included studies

First Author, Year of publication, Country	Level of performance	Sport or Discipline	Gender, Sample Size	Mean Age	Study Design	Assessment	Primary Outcome	Secondary Outcome
(Steinberg et al., 2014a); United Kingdom	Recreational	Dance	Female (n=588) Males (n=218)	13.5±2.3	Cohort	Questionnaires for participation, Injury prevalence: Self-reported, interview: menarche, anthropometric data	No significant association in the rate of injuries and chronological age (p=0.59)	Total months in the Centres for Advanced Training (OR= 1.044, 95% CI= 1.014-1.075) and hours per week in creative style practice (OR= 1.282, 95% CI= 1.068-1.539) - significantly associated with injuries for all dancers.
(Steinberg et al., 2011a); Israel	Recreational	Dance	Female (n=1082)	Range age 8-16	Case Series- retrospective	Interview, clinical assessment, anthropometric data, ROM, Dance technique	No association of injury was found with age of onset of menarche (P=0.34). No significant association of chronological age and overuse injuries.	Hours of practice per week associated with increased rate of injury (11.5 hours per week for the injured dancers vs 7.9 hours per week for the uninjured (P<0.001)).
(Baranto et al., 2006); Sweden	Not specified	Divers	Females (n=14) Males (n=6)	16.4±3.1	Cohort	MRI, injury data: questionnaires, self-assessment, Oswestry questionnaire	Association of back pain and chronological age.	n/a
(Loud et al., 2005); USA	Not specified	Mixed sport	Female (n=5461)	13.9±1.6	Cross-sectional- retrospective/ 4 years	Review of self-reported data of a National Study	Chronological age was strongly associated with a history of stress fracture.	Girls participating in ≥16 hours per week had a significantly higher risk of stress fracture (1.88; 95% CI:1.18-3.03).

Table 3-2. (cont.) Summary of included studies

First Author, Year of publication, Country	Level of performance	Sport or Discipline	Gender, Sample Size	Mean Age	Study Design	Assessment	Primary Outcome	Secondary Outcome
(Micheli and Fehlandt, 1992); USA;	Not specified	Mixed sport	Females (n=253) Males (n=193)	Range age 8-19	Case Series-retrospective	Review of cases	Association of growth and maturation with higher risk of injury occurrence.	n/a
(Thein-Nissenbaum et al., 2012); USA	Recreational	Mixed sport	Female (n=249)	15.3±1.1	Cross-sectional-retrospective	Injury prevalence & menstrual irregularity: Survey	Non-significant association of menstrual irregularity and overuse injuries (Odds ratio=2.7, 95% CI=0.8, 8.8)	n/a

3.3.3 Participants and setting

The total number of participants involved in all 23 studies was 10,146. Eight studies (8/23) included female (n=1151) and male participants (n=597) (Baranto et al., 2006, Bowerman et al., 2014b, Carter and Aldridge, 1988, Maffulli et al., 1992, Micheli and Fehlandt, 1992, Purnell et al., 2010, Steinberg et al., 2014a, Chang et al., 1995). Fifteen studies included single gender (n=8398); 14 out of these 15 studies included solely female 100% (n=8390) participants (Amaral et al., 2012, De Smet et al., 1994, Loud et al., 2005, Steinberg et al., 2011a, Caine et al., 1989, Lindholm et al., 1994, Steinberg et al., 2013, Thein-Nissenbaum et al., 2012, Warren et al., 1986, Warren et al., 1991, Goldstein et al., 1991, Kadel, 1992, Kolt and Kirkby, 1999, Steinberg et al., 2011b), whereas one out of these 15 studies included solely male <1% (n=8) participants (Carter et al., 1988). It was noted that from one big study cohort, the authors have published two reports (Steinberg et al., 2011a, Steinberg et al., 2011b); we have included in this review only the Steinberg *et al.* (Steinberg et al., 2011b) study (n=1336) and excluded the other report Steinberg *et al.* (Steinberg et al., 2011a) (n=1082). There were three studies that included control groups in the study design (Lindholm et al., 1994, Warren et al., 1991, Chang et al., 1995). Eleven studies (11/23) were in gymnastics (Amaral et al., 2012, De Smet et al., 1994, Caine et al., 1989, Carter and Aldridge, 1988, Lindholm et al., 1994, Maffulli et al., 1992, Kolt and Kirkby, 1999, Chang et al., 1995, Purnell et al., 2010, Carter et al., 1988, Goldstein et al., 1991). Two studies (2/23) were in ballet (Bowerman et al., 2014b, Kadel, 1992), and six studies (6/23) in dance (ballet, modern, jazz) (Steinberg et al., 2011a, Steinberg et al., 2014a, Steinberg et al., 2013, Warren et al., 1986, Warren et al., 1991, Steinberg et al.,

2011b). One study (1/23) was in diving (Baranto et al., 2006), and three studies (3/23) were in a mixture of sports but included aesthetic sports athletes in their cohorts where sport-specific results could be extracted (Loud et al., 2005, Micheli and Fehlandt, 1992, Thein-Nissenbaum et al., 2012).

3.3.4 Level of performance

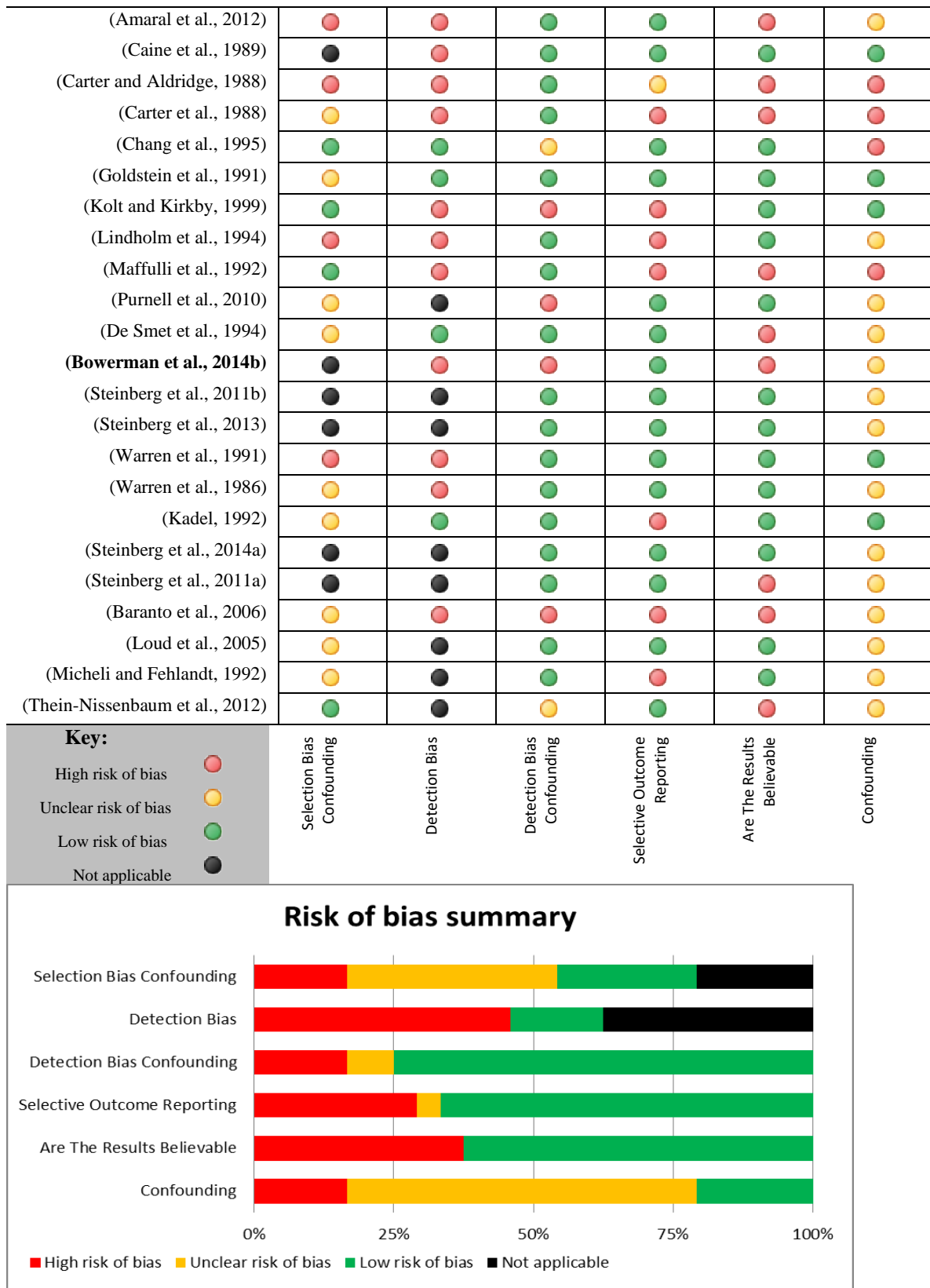
The level of performance (elite, pre-elite, sub-elite, professional, competitive, recreational) is reported according to the authors' classification. Thirteen studies (13/23) focused on elite/pre-elite/sub-elite/professional athletes (Amaral et al., 2012, Baranto et al., 2006, Bowerman et al., 2014b, De Smet et al., 1994, Caine et al., 1989, Lindholm et al., 1994, Maffulli et al., 1992, Warren et al., 1986, Warren et al., 1991, Chang et al., 1995, Goldstein et al., 1991, Kadel, 1992, Kolt and Kirkby, 1999), and one study (1/23) was on competitive athletes (Carter et al., 1988). Five studies (5/23) were on recreational athletes (Steinberg et al., 2011a, Steinberg et al., 2014a, Steinberg et al., 2013, Thein-Nissenbaum et al., 2012, Steinberg et al., 2011b), and two (2/23) were conducted on mixed populations of athletes (Carter and Aldridge, 1988, Purnell et al., 2010); finally, two studies (2/23) did not specify the level of performance (Loud et al., 2005, Micheli and Fehlandt, 1992).

3.3.5 Risk of bias

The risk of bias assessment results and summary are displayed in Figure 3-2, whereas the RTI-IB results are presented in detail in Appendix 12.1. Overall, the selected studies either showed high or unclear risk of bias in the selected quality areas as all 23 (23/23) scored on one or more key items either negative or unclear. In particular, confounding (i.e. retrospective data collection, length of study) was found to be the biggest risk of bias indicator as only five studies

(5/23) took relevant confounders into consideration (Warren et al., 1991, Kolt and Kirkby, 1999, Kadel, 1992, Goldstein et al., 1991, Caine et al., 1989). This together with the lack of blinding, either because it was not possible (9/23) due to the nature of the study (i.e. retrospective survey) or simply not included (11/23) increased bias due to not taking into account potential confounders that may have affected the reported results. Additionally, only three studies (3/23) reported a control group (Lindholm et al., 1994, Warren et al., 1991, Chang et al., 1995). This made the selection bias confounding the second highest risk of bias indicator. Detection bias confounding showed low risk of bias (18/23), however, methodologically more robust studies failed to report serious methodological flaws and, therefore, were considered as high risk of detection bias. Specifically, Baranto et al. (Baranto et al., 2006) used a higher specification magnetic resonance imaging scanner in the follow up compared to baseline. Bowerman et al. (Bowerman et al., 2014b) utilised inappropriate maturation monitoring protocols; namely the size of the foot. Sixteen studies (16/23) showed low risk of bias on selective outcome reporting, however, seven studies (7/23) showed high risk of bias by missing out important statistical analysis or values (Baranto et al., 2006, Carter et al., 1988, Kadel, 1992, Kolt and Kirkby, 1999, Lindholm et al., 1994, Maffulli et al., 1992, Micheli and Fehlandt, 1992), while for one study (1/23) there was unclear risk of bias as authors did not statistically analyse their observed data (Carter and Aldridge, 1988)

Figure 3-2. Risk of bias assessment results and Summary



Finally, 14 studies (14/23) showed low risk of bias in the believability of the results, however, the lack of confounding consideration and the nature of data collection through surveys and retrospective medical records decreased the validity of the reported results (Caine et al., 1989, Chang et al., 1995, Goldstein et al., 1991, Kolt and Kirkby, 1999, Lindholm et al., 1994, Purnell et al., 2010, Steinberg et al., 2011b, Steinberg et al., 2013, Warren et al., 1991, Warren et al., 1986, Kadel, 1992, Steinberg et al., 2014a, Loud et al., 2005, Micheli and Fehlandt, 1992).

3.3.6 Data Synthesis

Results of studies that were relevant to the primary and secondary objectives are summarised in Table 3-2. Due to the fact the studies were all cross-sectional, the reporting of outcomes in this section is broken down into relevant aesthetics sports/activities, rather than study design.

3.3.6.1 Gymnastics

Primary Outcome: Out of the 11 studies, two prospective studies reported a positive association of maturation (Caine et al., 1989) and age at menarche (Lindholm et al., 1994, Caine et al., 1989) with overuse injuries. Maturation rate was determined according to Tanner & Whitehouse (Tanner and Whitehouse, 1976). Six studies (Amaral et al., 2012, Carter and Aldridge, 1988, Chang et al., 1995, Kolt and Kirkby, 1999, Maffulli et al., 1992, Carter et al., 1988) reported a positive association of skeletal age, and overuse injuries. Two studies (Goldstein et al., 1991, Purnell et al., 2010), indicated a positive association of chronological age and overuse injuries. One study (De Smet et al., 1994) reported no association of chronological age and overuse injuries.

Secondary Outcomes: Three studies (Goldstein et al., 1991, Purnell et al., 2010, De Smet et al., 1994) reported a positive association of training load and overuse injuries.

3.3.6.2 Dance

Primary outcomes: Out of the nine studies that focused on dance (ballet, classical-ballet, modern and jazz), three (Steinberg et al., 2013, Warren et al., 1986, Warren et al., 1991) reported a positive association of age at menarche and overuse injuries. whereas two (Kadel, 1992, Steinberg et al., 2011a) reported no such association. Two studies (Bowerman et al., 2014b, Steinberg et al., 2011b) showed a positive association of growth and overuse injuries. Three studies (Steinberg et al., 2011b, Steinberg et al., 2013, Warren et al., 1991) reported a positive association of chronological age with overuse injuries whereas three studies (Kadel, 1992, Steinberg et al., 2014a, Steinberg et al., 2011a) reported no such association.

Secondary outcomes: Three studies (Kadel, 1992, Steinberg et al., 2014a, Steinberg et al., 2011a) reported a positive association of training load and overuse injuries.

3.3.6.3 Diving

Primary outcomes: One study (Baranto et al., 2006) reported a positive association of back pain and chronological age, and speculated that this could be due to overuse injuries to the spine during the growth-spurt.

Secondary outcomes: None reported

3.3.6.4 Mixed Sports

Primary outcomes: Out of the three studies that focused on mixed sports but included aesthetic sports, one (Micheli and Fehlandt, 1992) reported a positive association of maturation and

growth with higher risk of overuse injuries whereas one (Thein-Nissenbaum et al., 2012) reported a non-significant association. One study (Loud et al., 2005) reported that chronological age was strongly associated with overuse injuries.

Secondary outcomes: One study (Loud et al., 2005) reported a positive association of training load and overuse injuries.

3.4 Discussion

To the best of our knowledge, this is the first systematic review to primarily investigate the association between growth, maturation, and overuse injuries in aesthetic sports/activities. The secondary aim was to explore whether training load was associated with our primary objective. The review used a systematic manner to identify articles according to established guidelines (Moher et al., 2015).

Due to the heterogeneity of the included studies, 20 studies were pooled into three sports or activities (gymnastics, dance, and diving) whereas three studies were on mixed sport populations where specific results from aesthetic sports or activities could be separated and studied. Most participants were female and only three studies included a control group. There is a lack of current studies reporting the female and male participation ratio in aesthetic sports or the numbers of participants according to level of performance nationally and internationally. Moreover, the timing of growth and maturation differs between genders, (Bergeron et al., 2015a) therefore, our results cannot be generalised for all levels of performance or all genders.

A positive association between growth, maturation, skeletal and chronological age with overuse injuries was found in 19 studies. In gymnastics, the three studies that reported a lower risk of bias showed an association of skeletal age, (Amaral et al., 2012) chronological age, (Chang et al., 1995, Goldstein et al., 1991) and training load (Goldstein et al., 1991) with overuse injuries; only one study took into account the effects of maturation confounders, such as age at menarche (Amaral et al., 2012). The two studies that focused on chronological age and training load, did not give clear indication of the maturation status of the participants (Chang et al., 1995, Goldstein et al., 1991). In dance, diving and mixed sports studies, due to the cross-sectional design of the studies and their high risk of bias, no robust conclusion can be drawn about these associations. However, it is worth noting that in dance, the studies led by Steinberg (Steinberg et al., 2014a, Steinberg et al., 2011a, Steinberg et al., 2013, Steinberg et al., 2011b) utilised large cohorts of participants with contradictory results in terms of the associations between growth, maturation and overuse injuries. This contradiction could mainly be accounted due to the different hypothesis the two studies had as they referred to the same sample of participants (Steinberg et al., 2011b, Steinberg et al., 2011a). In the one study (Steinberg et al., 2011b) the authors characterized injuries in non-professional dancers, whereas in the other (Steinberg et al., 2011a) they investigated joint range of movement, body structure, anatomic anomalies, dance technique, and dance discipline in recreational dancers with paratenonitis. Moreover, in the “Paratenonitis...” study (Steinberg et al., 2011a) the inclusion of probing questions during the screening of the participants, may have introduced detection bias. Interestingly, in their study they reported no association of chronological age and paratenonitis, which is an overuse injury, whereas they reported an association of chronological age and injuries, both overuse and acute, in their in their “Injury Patterns. . .” study with the same cohort (Steinberg et al., 2011b).

In mixed sports, the study of Loud and colleagues (Loud et al., 2005) included a very large national cohort (n=5461 female athletes) and concluded that chronological age was strongly associated with stress fractures in all multivariate models.

Furthermore, six of the studies reported an association of training load and overuse injuries; interestingly half of the studies did not report an association of growth, maturation and chronological age with overuse injuries, however, their findings are inconclusive due to the large variance of training loads which ranges between 8-16 hours per week for gymnastics, (Goldstein et al., 1991, Purnell et al., 2010, De Smet et al., 1994) >11.5-25 hours per week in dance, (Kadel, 1992, Steinberg et al., 2014a, Steinberg et al., 2011a) and >16 hours per week in a mixed sport study (Loud et al., 2005).

When interpreting the outcomes of this review, one should not only be aware of the variation in the participants' level of performance, but also the setting, duration of follow up, focus, terminology, and assessment methods each study used. This systematic review showed inconsistency in how the included studies accounted for the important confounding associations of growth, maturation with overuse injuries in aesthetic sports/activities. Of the six studies that reported an association of skeletal age with overuse injuries, (Amaral et al., 2012, Carter and Aldridge, 1988, Chang et al., 1995, Kolt and Kirkby, 1999, Maffulli et al., 1992, Carter et al., 1988) only two studies (Amaral et al., 2012, Carter et al., 1988) reported skeletal age in relation to chronological age. Inconsistencies also existed in the methods used for the assessment of skeletal maturation. The Tanner-Whitehouse 3, utilised by Amaral and colleagues, (Amaral et al., 2012) a radiographic skeletal maturation assessment method that is used prospectively may not be cost effective or easily applicable for large cohorts (Tanner,

2001). On the other hand, older studies utilised different radiographic assessment methods, (Carter et al., 1988, Carter and Aldridge, 1988) a factor that makes the comparison of their results very challenging. Moreover, two studies (Steinberg et al., 2011b, Bowerman et al., 2014b) in dance that reported a positive association of growth and overuse injuries, differ in their methodological approach. Steinberg *et al.* (Steinberg et al., 2011b) hypothesise the association from retrospective data of chronological age and injury history of a large group of recreational dancers (n=1336). Bowerman *et al.*, (Bowerman et al., 2014b) on the other hand, prospectively observed a small group (n=46) of dancers for six months, however, the period was very short for any observations on the effect/association of growth and maturation on/with overuse injuries and the methodology of growth and maturation monitoring was flawed. The foot measurement protocol was not developed to monitor growth in adolescents and the Tanner stages, i.e. breast development and pubic hair, cannot be grouped between genders, as they correspond to different maturity timing and status. Also, the methods utilised by the available studies to assess overuse injuries and/or the confounding factors that may affect the prevalence of overuse injury in aesthetic sports, are characterised by different strengths and limitations. Furthermore, given the fact that overuse injuries are always reported after the event, recall bias is a major limitation both for prospective and retrospective studies.

Growth and maturation monitoring ideally need to be investigated through longitudinal research (Malina et al., 2015). Even though, it has been argued that there is no “gold standard” method of maturation assessment, (Malina et al., 2015) this review has indicated fundamental flaws in the methodology of the included studies. This increased the risk of bias as none of the 23 studies were assessed as low risk of bias in all domains (Figure 3-2).

Even though blinding of both participants and researchers can rarely be achieved in observational studies, steps can and should be taken to ensure blinding of outcomes assessors in order to minimise detection bias. Only four studies (Chang et al., 1995, Goldstein et al., 1991, De Smet et al., 1994, Kadel, 1992) did so, however, three of these four studies included blinding of outcomes, (Chang et al., 1995, Goldstein et al., 1991, De Smet et al., 1994) whereas Kadel *et al.*, (Kadel, 1992) included blinding but only in the selection of participants. In addition, none of the selected studies reported measurement errors for their measurements.

These identified methodological concerns may account for some of the observed equivocal and inconclusive evidence. For example, ulnar variance (UV) was the main primary outcome in three gymnastics studies (Amaral et al., 2012, De Smet et al., 1994, Chang et al., 1995) given that overuse injury is common in this sport. Their results, however, were contradictory. The cross-sectional designs and the different assessments utilised in two of the studies, (Amaral et al., 2012, De Smet et al., 1994) may have accounted for these disparate results. However, even though in Chang *et al.*, (Chang et al., 1995) the researchers included a control group and found significant difference ($p < 0.05$) between the two groups in UV prevalence, the question of whether the variance is associated to restricted growth of the radius and not to ulnar overgrowth needs to be considered. Other disciplines, like dance, are also characterised by contradictory outcomes. Specifically, in a cross-sectional study ($n=54$; mean age= 20.2 ± 4.4 yrs) in professional dancers, no association was reported between age at menarche with stress fractures, (Kadel, 1992) but such an association was reported in a cross-sectional study ($n=75$; mean age= 24.3 ± 4.1 yrs) (Warren et al., 1986) and in a case control study ($n=98$; mean age= 21.87 ± 4.5 yrs) (Warren et al., 1991). All three studies, however, relied on retrospective data

on injury history from interviews and questionnaires, therefore, recall bias may have decreased the validity of these results (Gallagher et al., 2017).

A recent systematic review on self-reported data states that there is no established athlete-reported outcome measure of the effects of injury/illness on performance in sport (Gallagher et al., 2017). Included studies in this review reported outcomes from self-reported data collected via tools where the validity and reliability had not been tested or reported (Chang et al., 1995, Thein-Nissenbaum et al., 2012, Purnell et al., 2010). Even though ‘one-size does not fit all’ in surveillance methods, (Gallagher et al., 2017) the need for consensus-based practice in injury prevalence for aesthetic sports is paramount.

Research investigations in adolescents need to control for the effects of growth and maturation, in order to minimise its confounding effects (Mirwald, 2002). Monitoring should not only include growth and maturation in relation to chronological age, but also training load, which based on the results of this systematic review also seems to be associated with overuse injuries. However, none of the reported studies clearly define training load. Recent studies in sports suggest that higher loads, (Killen et al., 2010) large increases in load too soon, (Killen et al., 2010) and imbalanced stress and recovery ratio (Brink et al., 2010) are all associated with greater injury rates. However, simply reporting hours/years of training is a limited indicator of training intensity (Malina et al., 2015). A clearer understanding is needed of what the individuals are doing in the training of aesthetic sports/activities, and how this training affects them both physiologically and psychologically. Monitoring and understanding the association of growth, maturation, training load and overuse injuries may have a significant impact on health associated costs. The cost of dance related injuries in a professional company has been

compared with that of a college athletic department or a professional sport team (Garrick and Requa, 1993). In addition, reducing the incidence as well as the risk of overuse injuries minimises the risk for future injuries (Caine et al., 1989, DiFiori, 2010a) and, therefore, promotes better athlete's health and maximisation of performance potential.

3.4.1 Strength and Limitations

The current review used a systematic manner to identify articles according to established guidelines (Khan et al., 2003, Liberati et al., 2009, Moher et al., 2015) while a well-established tools to evaluate the included studies was utilised (von Elm et al., 2014, Viswanathan et al., 2013). An attempt to minimise publication bias was made by carrying out a sensitive search of multiple databases, however, even though the search was comprehensive and studies that were not published in English were not excluded, the possibility that there might be studies that have been missed cannot be rule out. Bias in the review process was minimised by having at least two authors independently and in duplicate screening studies for inclusion and in the assessment of the risk of bias.

A limitation of the current review includes the use of only published literature; grey literature was not included in the search and therefore, there is a potential of publication bias in the selected approach. However, including grey literature may, in itself, introduce bias.

3.5 Conclusion

The findings of this systematic review indicate that the current knowledge on the relationship of growth, maturation and overuse injuries in aesthetic sports/activities relies on evidence from

observational studies with significant limitations. The variation in the participants' level of performance, sample size, duration of follow up, focus, terminology and assessment methods each study used, together with the increased levels of risk bias due to either methodological constraints or negligence cannot provide us with clear outcomes on whether the growth and maturation process or/and the training load are associated with overuse injuries in aesthetic sports/activities. The cross-sectional, and for the majority of the studies, retrospective design and the high overall risk of bias of the available studies about growth, maturation, skeletal and chronological age and overuse injuries warrant further investigations in this field, particularly given the detrimental effects of overuse injuries on both the athlete and health services. Monitoring maturation longitudinally and prospectively with appropriate and validated assessments, together with injury surveillance with clear injury definitions could potentially provide clinicians and practitioners with valuable information. This knowledge can then be applied to develop and implement injury prevention strategies to protect adolescents in aesthetic sports/disciplines from overuse injuries. The etymology of the word *overuse* is itself giving the solution to the problem. Growth and maturation cannot be controlled but can only be accounted for. Given the fact that organised sport is an adult-controlled environment, practitioners need to monitor this biological process and plan accordingly the intensity, volume, and frequency of the activity. All of these parameters can be controlled, making sure the plan is flexible, adaptable, and safe for the adolescents.

4 The relationship of injury incidence with countermovement jump in adolescent ballet dancers: a prospective cross-sectional study

4.1 Background

It is well documented that there is high incidence of injuries in elite adolescent (Caine et al., 2015) and professional ballet dancers (Jacobs et al., 2012, Smith et al., 2015) with female dancers sustaining more injuries than their male counterparts (Allen et al., 2012, Ekegren et al., 2014). Most of the injuries are consistently reported to be of overuse onset and the most affected region has been reported to be the lower limb (Jacobs et al., 2012, Caine et al., 2015, Ekegren et al., 2014, Gamboa et al., 2008, Nilsson et al., 2001, Leanderson et al., 2011, Steinberg et al., 2011b). Associated injury risk factors in professional dancers have been identified to be gender, age, number of years of training, ranking, seasonal timing, frequency or intensity of training, fatigue, previous injury (Jacobs et al., 2012). Similarly, in pre-professional dancers injury history (lower limb) was a significant predictor of lower extremity injury in modern and ballet dancers (Wiesler et al., 1996). Older adolescents are thought to be more susceptible to injuries due to risk factors associated with growth and maturation (Poggini et al., 1999).

Research has indicated that low levels of aerobic fitness (Twitchett et al., 2010) and lower extremity muscle strength were associated with high degree of injuries (Koutedakis et al., 1997a). It has been reported that injured pre-professional dancers have lower strength values on the lower extremity than non-injured dancers (Gamboa et al., 2008). In professional dancers, the largest proportion of injuries were related to jumping activities (Allen et al., 2012).

Jumping is an important element of ballet training. Anecdotally it has been reported that young elite ballet dancers may perform more than 200 jumps in a regular ballet class every day, with the main focus to master the aesthetic look of complex aerial positions. In addition, lower extremity overuse injuries have been reported to be associated with increased exposure to repetitive jumping in ballet dancers (Allen et al., 2012). Interestingly, the height of the jump is not part of the assessment criteria when appraising the development of a young dancer. The assessment of jumping ability through the vertical jump test, however, has been used as part of research in professional (Wyon et al., 2007), adolescent recreational male (Pekkarinen et al., 1989) and female ballet (Claessens et al., 1987, Twitchett et al., 2010) and female contemporary (Angioi et al., 2009) dancers.

The vertical jump test is a component of test batteries utilised to assess physical ability (Taylor et al., 2010). It has been argued that the maximum vertical jump height is a valid measure of the maximum power output of the lower limb musculature (Baker et al., 2001, Markovic and Jaric, 2007, Samozino et al., 2008), in populations of different age, gender and training status (Asmussen and Bonde-Petersen, 1974, Davies et al., 1984, Taylor et al., 2010, Castagna and Castellini, 2013, Laffaye et al., 2014, Holden et al., 2015). Since the measurement of physiological parameters is not part of the assessment of the young dancer, no reference data on the jump height for this population exist, therefore, the evaluation of this performance variable cannot be conducted either against a performance criterium level or any normative data (Taylor et al., 2010).

Research on the association of injury incidence and muscular power in dance is scarce. A longitudinal study with female ballet dancers did not find any association between lower

extremity muscle power and injuries (Twitchett et al., 2010). On the contrary, Angioi and colleagues observed a negative correlation between vertical jump and days off dance in pre-professional contemporary and ballet dancers (Angioi et al., 2009). Two experimental studies that also assessed this relationship in pre-professional dancers did not find any association between injuries and muscle power, assessed with standing broad jump (Mistiaen et al., 2012, Roussel et al., 2014). The study by Mistiaen and colleagues, however, was characterised by major methodological flaws, such as lack of control group, or standardisation of tests and procedures, dropout and small sample size, therefore, their results need to be considered with caution (Mistiaen et al., 2012).

Traditionally, the young dancers are assessed for their physical attributes (i.e. turnout, ankle flexibility) when they enter vocational education but there are no guidelines on whether any physiological markers (i.e. jump height) are associated with injury incidence.

4.2 Aims and hypothesis

The aim of this study, therefore, was to investigate the associations of injury incidence and countermovement jump in adolescent ballet dancers. This longitudinal study was conducted with a larger sample size than previous research, with standardised methods (i.e. injury reporting, outcome assessment protocols).

The null hypothesis was that there will be no significant association of injury incidence and countermovement jump. Moreover, the null hypothesis for the secondary outcomes was that there would be no gender, age and maturity status differences in both injury incidence and the countermovement jump.

4.3 Methods

4.3.1 Study design and settings

A prospective cross-sectional design was used for this study. The study was conducted in a vocational ballet school with elite adolescent dancers in Birmingham, United Kingdom, between September 2016 and February 2017. Informed consent was acquired from all guardians and participants prior to the study. The study received ethical clearance from the University of Wolverhampton (Appendix 12.3).

4.3.2 Outcomes

The primary outcome was to investigate the association between injury incidence and countermovement jump, whereas the secondary outcomes were the investigation of gender, age, and maturity status differences in injury incidence.

4.3.3 Participants

One hundred and seventy-nine elite ballet dance students who were enrolled at the school by September 2016 took part in this study. Students who enrolled at the school later were excluded from the study. The group was divided into eight age groups starting at the age of 12 year of age. Male and female students train the same number of hours in the week, but classes are split by age and gender. Body conditioning was based on floor-based Pilates exercises for one hour per week.

4.3.4 Equipment

Jump height (JH) was measured with an Optojump Next system (Microgate, Version 1.10.19).

The Optojump is a photocell system that consists of two bars, a transmitting and receiving one that are one metre long and are equipped with

33 optical light-emitting diodes (LEDs)

(Figure 4-1). The transmitting LEDs are

continuously communicating with the

corresponding receiving LEDs. The LEDs

are positioned at 0.3cm from the ground and

at 3.125cm interval on the bar. Flight time is

calculated through the break of them beam

that switches on and off the chronometer on

the computer (manufacturer's declared accuracy: $1 \times 1000 \text{ s}^{-1}$) (Castagna and Castellini, 2013,

Castagna et al., 2013). The Optojump Next has demonstrated excellent validity and reliability

scores, ICC range 0.997-0.998 and 0.982-0.989 respectively. More specifically, test-retest

reliability for the CMJ test with hands akimbo is excellent ICC= 0.989 (95% CI: 0.973-0.996),

CV= 2.2% (Glatthorn et al., 2011).



Figure 4-1. Optojump photocell system

4.3.5 Procedure

Height measurement to the closest millimetre (0.1cm) with a portable stadiometer (SECA

213) and weight measurements to the closest gram (0.1kg) with a wireless column scale (SECA

704s) were obtained. BMI (kg/m^2) was then calculated (mass in kg divided by height in m

squared) (Keys et al., 1972). All the tests took place in the first two weeks of September 2016.

As reported in previous studies, the testing took place in a thermoregulated room (temperature 19°C) and on the same floor (rubber floor) (Rössler et al., 2016a). Testing commenced with a warm-up comprising of two minutes light cardiovascular exercise followed by dynamic stretches targeting the big muscles of the lower body (Flanagan et al., 2008). All participants were familiar with the test as they were routinely used in order to monitor their fitness (Cloak et al., 2014). Parental height was obtained from the students' personal data files, as this was data the school had already collected.

4.3.6 Countermovement Jump

The participants performed three countermovement jumps (CMJ) bilaterally in a non-fatigued state (Flanagan et al., 2008). Optojump Next measured the flight-time for the CMJ and automatically calculated the jump height. The highest value was used for analysis (Castagna and Castellini, 2013). For the jump the participants were instructed to stand upright, with their feet hip width apart, and keep their hands akimbo throughout the jump, to restrict upper body interference (Lees et al., 2004, Hara et al., 2006, Hara et al., 2008). To begin the test, the participants performed a squat to a self-selected depth followed by a fast upward vertical movement, triple extending at the hips, knees and ankles with an explosive intent to jump as high as possible (Bishop et al., 2018). The participants were also instructed to remain with the knees and ankles extended and land in the same position and location in order to avoid horizontal displacement which could have an effect on flight time (Chaouachi et al., 2017). If the participants deviated from the instructions, they had to re-take the jump after a 60-second rest period (Bishop et al., 2018).

4.3.7 Injury Reporting

All injuries were recorded prospectively by the in-house physiotherapists from September 2016 to February 2017. Both practitioners had been working at the school for six years and had a lot of experience with this population. A time-loss definition of injury was used to report the injuries, where by “any injury that prevented a dancer from taking a full part in all dance-related activities that would normally be required of them for a period of equal to or greater than 24 hours after the injury was sustained” (Allen et al., 2013). An injury that resulted from a specific identifiable event was classified as *traumatic*, whereas an injury that was caused by repeated microtrauma without a single identifiable event responsible for the injury was classified as *overuse*. Finally, an injury of the same type and at the same site of the first episode injury, that occurred after the dancer had returned to full participation from the initial injury within two months, was classified as *recurrent* (Allen et al., 2013).

The injuries were classified into specific body area categories according to the Orchard Sports Injury Classification System (OSICS Version 10) (Rae and Orchard, 2007). The term *incidence* was used to refer to the number of new occurrences of injury during the period of the study (Knowles et al., 2006). A descriptive analyses of the incidence proportion (IP), clinical incidence, and the injury incidence rate (IR) was conducted. The incidence proportion refers to the average probability, across all dancers to be injured during an academic year (or years) of participation or the period of the study, whereas clinical incidence refers to the number of injuries per dancer during an academic year of period of the study. The injury incidence rate was calculated based on time-based exposure (i.e. dance hours) (Knowles et al., 2006).

4.3.8 Dance Hours

The dance hours were calculated according to the weekly timetable of the school. The holiday weeks for half-term in October and for Christmas in December and January were excluded from the calculations (Bronner et al., 2006). Dance hours were calculated for the entire sample, for gender and age groups separately (Ekegren et al., 2014).

4.3.9 Maturity Status

Maturity status was calculated using the Khamis-Roche model which is utilizing the percentage of predicted adult stature/height (PAH) (Khamis and Roche, 1994). This method is based on linear regression of the average stature of the two parents and current values of stature, and weight of the individual (Khamis and Roche, 1994). Using the PAH at the time of the observation, the participants were then grouped into maturity categories. These are 1) Pre-pubertal (<85% of PAH), 2) Early pubertal (>85-90% of PAH), 3) Mid-pubertal (90-95% of PAH) and 4) Late pubertal (>95% of PAH) (Cumming et al., 2017). Due to the fact the regression model stops at the age of 17.5 years for both males and females, any students above this age were classified as being at the phase of Early adulthood.

4.3.10 Statistical analyses

Results are presented for the entire group, for each gender and for each of the age and maturation categories (Rössler et al., 2016b). Statistical analyses were mainly of a descriptive nature (Rössler et al., 2016b). The chronological age has been rounded up. The formulas for the calculation of the epidemiologic incidence proportion, clinical incidence, injury incidence rate per 1000 dance-hours, together with their respective standard error calculations are presented in (Table 4-1) (Knowles et al., 2006).

Table 4-1. Formulas for calculation of incidence measures

Incidence Measure	Estimated Incidence	Formula for Estimated Standard Error	95% Confidence intervals
<i>Incidence Proportion (IP)</i>	$IP = (\Sigma \text{ injured dancers } \div \Sigma \text{ dancers})$	$SE(IP) = \frac{\sqrt{IP \times (1 - IP)}}{\Sigma \text{ dancers}}$	$(IP \pm 1.96 \times (SE))$
<i>Clinical Incidence</i>	$ClinInc = (\Sigma \text{ injuries } \div \Sigma \text{ dancers})$	Same as IP	Same as IP
<i>Incidence Rate (IR)</i>	$IR = (\Sigma \text{ injuries } \div \Sigma \text{ dance hours}) \times 1000$	$SE(IR) = \frac{\sqrt{\# \text{ injuries}}}{\Sigma \text{ dance hours}}$	$[(IR \pm 1.96 \times (SE)) \times 1000]$

Pearson's correlation coefficients were used to assess the associations between CMJ and injury incidence. Differences between two groups (male-female, or same age group) were assessed with independent t-tests, whereas differences with more than two groups (age or maturity status) were assessed with (2x8) ANOVAs. Bonferroni-adjusted pairwise comparisons identified the specific differences between the groups. Crosstabulations were utilised to report the injuries within the different age groups and gender, classification, region, and body part. Chi-square test of independence was calculated to compare the injury incidence between genders. Alpha level was set at 0.05 for all tests. Statistical significance was also evaluated according to whether or not the 95% confidence intervals (95% CI) contained the null value (1.0 for ratio, 0 for risk difference) (Higgins and Green, 2011).

The formula calculations were conducted in Excel (Microsoft Excel for Office 365). Descriptives, correlations and crosstabulations were conducted using Jamovi Version 1.0

(Retrieved from <https://www.jamovi.org>), whereas T-tests and ANOVAs were performed with SPSS (Version 24.0. Armonk, NY: IBM Corp.).

4.4 Results

One-hundred and seventy-nine dancers (mean \pm SD; 15.3 \pm 2.37yrs; 162 \pm 10.9cm; 48.2 \pm 10.7kg) participated in this study. Sixty-six students remained injury-free whereas 113 dancers sustained an injury giving an incidence proportion IP= 63.1% (95% CI: 56, 70.2). Thirty-two dancers (IP= 28.3%; 95% CI: 20, 36.6) sustained two injuries, seven (IP= 21.9%; 95% CI: 7.6, 36.2) sustained three injuries and one (IP= 14.3%; 95% CI: -11.6, 40.2) sustained four injuries.

The overall clinical incidence was 0.84 (95% CI: 0.11, 1.56) injuries per dancer. Over the period of the study (19 weeks) the total dance hours for all the dancers were 77,957 (mean \pm SD; 9,745 \pm 3,383h). One hundred and fifty-one injuries were reported, 37 of these were recorded in September. The timing (month) of the

injuries can be seen in Figure 4-2. The overall injury incidence rate was 1.94/1000h (95% CI: 1.63, 2.25). One hundred and sixteen injuries were classified as overuse (73%), 25 injuries were classified as traumatic (18%), whereas ten injuries (4%) did not have a

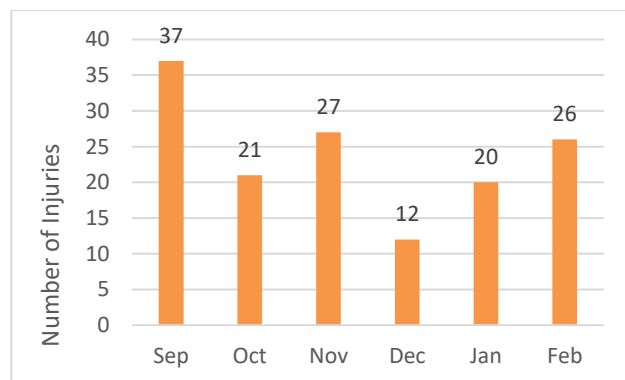


Figure 4-2. Number of injuries in the months of the year.

classification. Six injuries of the 116 overuse injuries (3%) were recurrent (Figure 4-3).

Most injuries were sustained on the lower limb (86%), followed by the trunk (11%) and the upper limb (7%). The ankle (33%), knee (18%), and foot (17%), were the most affected areas, followed by the lower leg (9%) and hip (9%). There was no association between CMJ (mean \pm SD; 27 \pm 6.95cm) and the injury incidence ($r = -0.038$; $p = .622$, 95% CI: -0.188, 0.113).

4.4.1 Gender Differences

The study group consisted of 68 male and 111 female dancers, anthropometric data can be found in Table 4-2. Forty-four male dancers and 69 females sustained at least one injury with an overall incidence proportion of 24.6% (95% CI: 18.3, 30.9) and 38.5% (95% CI: 31.4, 45.7) respectively ($\chi^2(7) = 6.41$, $p = .493$). The clinical incidence for the male was 0.88 (95% CI: 0.8, 0.96) injuries per dancer, whereas for the female it was 0.83 injuries (95% CI: 0.76, 0.9) (Table 4-4). Overall dance hours for males were 28,671 hours, with a total of 59 injuries reported and an injury rate of 2.03/1000h (95% CI: -0.52, 0.52). For the female dancers, the overall dance hours were 49,286 hours, with a total of 92 injuries reported and an injury rate of 1.88/1000h (95% CI: 1.5, 2.27).

Table 4-2. Descriptives for age, height, weight and BMI for males, females, and all age groups

Gender	N	Year Group	Chronological Age	Height	Weight	BMI
Male	68		15.2±2.49	165±12.6	51.5±12.5	18.3±3.12
Female	111		15.4±2.31	161±9.26	46.2±9.04	17.7±2.02
Age groups	21	7	11.7±.34	147±6.32	34.4±5.20	15.8±1.56
	24	8	12.6±.31	154±8.49	40.3±7.04	16.8±1.51
	20	9	13.7±.30	158±7.95	42.8±6.30	16.9±1.32
	24	10	15.0±.38	165±7.73	47.8±6.39	17.4±1.39
	20	11	15.7±.31	168±6.51	52.7±6.97	18.5±1.42
	22	12	16.6±.53	170±8.00	54.8±8.79	18.7±1.52
	25	13	17.8±.48	166±8.07	55.0±7.85	19.1±4.38
	23	14	18.8±.39	168±9.26	57.7±10.6	20.3±1.85

Table 4-3. Male and female incidence proportion for the different age groups

Age (years)	Total Students (n)	Injured Dancers (n)	Incidence Proportion (95% CI)	Male		Female	
				Injured Dancers (n)	Incidence Proportion (95% CI)	Injured Dancers (n)	Incidence Proportion (95% CI)
12	21	10	47.6% (26.2%, 68.9%)	5	23.8% (5.6%, 42%)	5	23.8% (5.6%, 42%)
13	24	12	50% (29.9%, 70%)	6	25% (7.7%, 42%)	6	25% (7.7%, 42%)
14	20	12	60% (38.5%, 81.4%)	4	20% (2.5%, 37.5%)	8	40% (18.5%, 61.3%)
15	24	17	70.8% (52.6%, 89%)	8	33.3% (14.4%, 52.2%)	9	37.5% (18.1%, 56.9%)
16	20	14	70% (49.9%, 90%)	7	35% (14.1%, 55.9%)	7	35% (14.1%, 55.9%)
17	22	15	68.2% (49.7%, 87.6%)	3	13.6% (-0.7%, 28%)	12	54.5% (33.7%, 75.4%)
18	25	16	64% (45.2%, 82.8%)	4	16% (1.6%, 30.4%)	12	48% (28.4%, 67.6%)
19	23	17	73.9% (55.9%, 91.9%)	7	30.4% (11.6%, 49.2%)	10	43.5% (23.2%, 63.7%)
Total	179	113	63.1% (56.1%, 70.2%)	44	24.6% (18.3%, 30.9%)	69	38.5% (31.4%, 45.7%)

Females sustained more injuries than males, however, the differences between the two genders were not statistically significant [$t(177) = .307$, $p = .759$, 95% CI: -0.211, 0.289] (Figure 4-3).

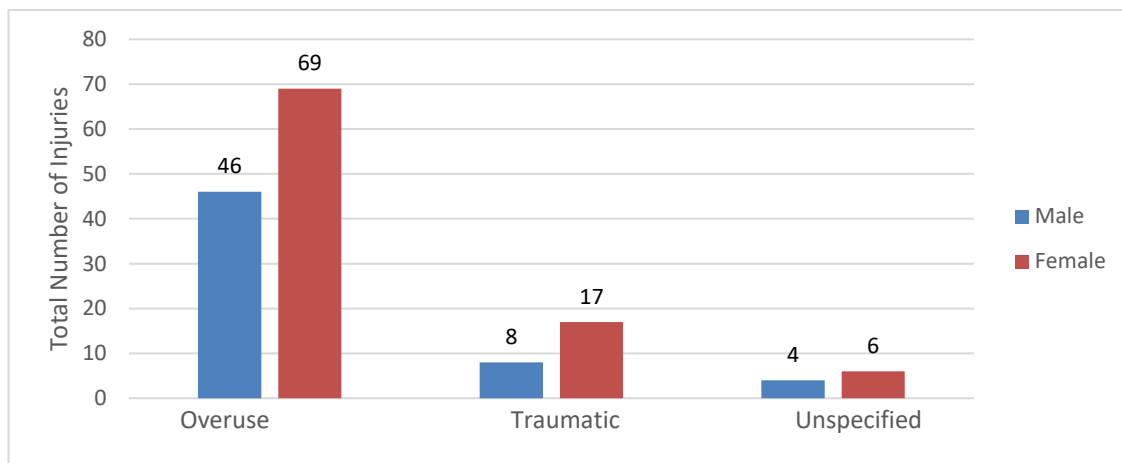


Figure 4-3. Total overuse, traumatic and unspecified injuries for male and female dancers

Table 4-4. Clinical incidence for all dancers and gender

Age (years)	Dancers (n)	Total Injuries	Clinical Incidence (95% CI)	Male			Female		
				Dancers (n)	Injuries (n)	Clinical Incidence (95% CI)	Dancers (n)	Injuries (n)	Clinical Incidence (95% CI)
12	21	12	0.57 (-0.4, 1.54)	9	6	0.67 (0.36, 0.97)	12	6	0.5 (0.22, 0.78)
13	24	13	0.54 (-0.43, 1.52)	11	7	0.64 (0.35, 0.92)	13	6	0.46 (0.19, 0.73)
14	20	19	0.95 (0.52, 1.38)	6	10	1.67 (-)	14	9	0.75 (0.51, 1)
15	24	19	0.79 (0, 1.59)	10	10	1 (1, 1)	14	9	0.64 (0.39, 0.89)
16	20	17	0.85 (0.15, 1.55)	10	8	0.8 (0.55, 1.05)	10	9	0.9 (0.71, 1.09)
17	22	25	1.14 (-)	5	4	0.8 (0.45, 1.15)	17	21	1.24 (-)
18	25	22	0.88 (0.24, 1.52)	7	5	0.71 (0.38, 1.05)	18	17	0.94 (0.84, 1.05)
19	23	24	1.04 (-) [†]	10	9	0.9 (0.71, 1.09)	13	15	1.15 (-)
Total	179	151	0.84 (0.13, 1.56)	68	59	0.88 (0.8, 0.96)	111	92	0.83 (0.76, 0.9)

Table 4-5. Injury rate per 1000 hours of dance for both genders split by chronological age

Age (years)	Dance Hours per week	Study Length (weeks)	Total Dance Hours	Dancers (n)	Study Dance Hours	Total Injuries	Rate/ 1000h dance (95% CI)	Male				Female			
								n	Study Dance Hours	Total Injuries	Rate/ 1000h dance (95% CI)	n	Study Dance Hours	Total Injuries	Rate/ 1000h dance (95% CI)
12	19	19	361	21	7,581	12	1.58 (0.69, 2.48)	9	3,249	6	1.85 (-1.48, 1.48)	12	4,332	6	1.39 (0.27, 2.49)
13	19	19	361	24	8,664	13	1.50 (0.69, 2.32)	11	3,971	7	1.76 (-1.3, 1.3)	13	4,693	6	1.28 (0.26, 2.3)
14	19	19	361	20	7,220	19	2.63 (1.45, 3.81)	6	2,166	10	4.62 (-2.86, 2.86)	14	5,054	9	1.78 (0.62, 2.94)
15	17	19	323	24	7,752	19	2.45 (1.35, 3.55)	10	3,230	10	3.10 (-1.92, 1.92)	14	4,522	9	1.99 (0.69, 3.29)
16	17	19	323	20	6,460	17	2.63 (1.38, 3.88)	10	3,230	8	2.48 (-1.71, 1.71)	10	3,230	9	2.79 (0.97, 4.61)
17	27	19	513	22	11,286	25	2.22 (1.35, 3.08)	5	2,565	4	1.56 (-1.53, 1.53)	17	8,721	21	2.41 (1.38, 3.44)
18	27	19	513	25	12,825	22	1.72 (0.99, 2.43)	7	3,591	5	1.39 (-1.22, 1.22)	18	9,234	17	1.84 (0.97, 2.72)
19	37	19	703	23	16,169	24	1.48 (0.89, 2.08)	10	7,030	9	1.28 (-0.84, 0.84)	13	9,139	15	1.64 (1.5, 2.27)
			Total	179	77,957	151	1.94 (1.63, 2.25)	68	28,671	59	2.03 (-0.52, 0.52)	111	49,286	92	1.88 (1.5, 2.27)

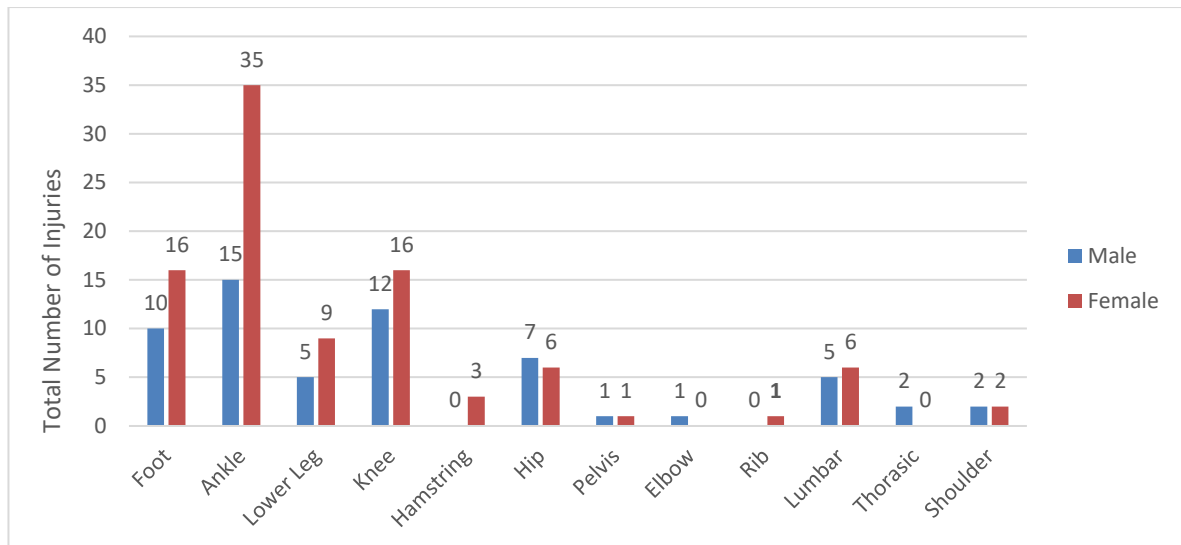


Figure 4-4. Total number of injuries for injured body parts for males and females

Females reported higher incidence of ankle, foot, lower leg, and knee injuries than the males. Lumbar spine (7%) injuries were recorded for both males and females. Hamstring (2%) injuries were recorded for female dancers only, whereas thoracic spine (1%) injuries were recorded only for the males. Shoulder (3%), pelvis (1%), elbow (1%) and rib (1%) injuries were recorded for both males and females (Figure 4-4).

Data on CMJ were available from 169 injury-free students ($n=105$ female). Table 4-6 presents the CMJ mean scores, standard error and 95% confidence intervals, for all the male and female age groups and the graphical representation of this data can be seen in Figure 4-5. A 2x8 ANOVA revealed statistically significant difference between males and females $F(1, 153)=119.96$, $p < .001$, $\eta_p^2 = .439$. Post hoc pairwise comparisons revealed that older females (>15 years old) had lower CMJ scores than their male counterparts, for details please see Table 4-7.

Table 4-6. Male and female estimated mean CMJ scores, standard error and 95% confidence intervals, split by age

Age	Male				Female			
	Mean	SE	95% Confidence Interval		Mean	SE	95% Confidence Interval	
			Lower	Upper			Lower	Upper
12	24.7	1.53	21.7	27.7	23.4	1.39	20.7	26.2
13	25.8	1.39	23.1	28.5	23.5	1.28	21.0	26.0
14	27.4	1.88	23.7	31.1	23.1	1.23	20.8	25.6
15	30.2	1.45	27.3	33.0	22.8	1.23	20.4	25.2
16	35.6	1.45	32.7	38.4	24.5	1.45	21.6	27.4
17	31.2	2.06	27.1	35.3	24.8	1.12	22.6	27.0
18	42.5	1.74	39.1	45.9	25.0	1.08	22.9	27.2
19	41.3	1.9	37.5	45.0	25.1	1.63	21.9	28.3

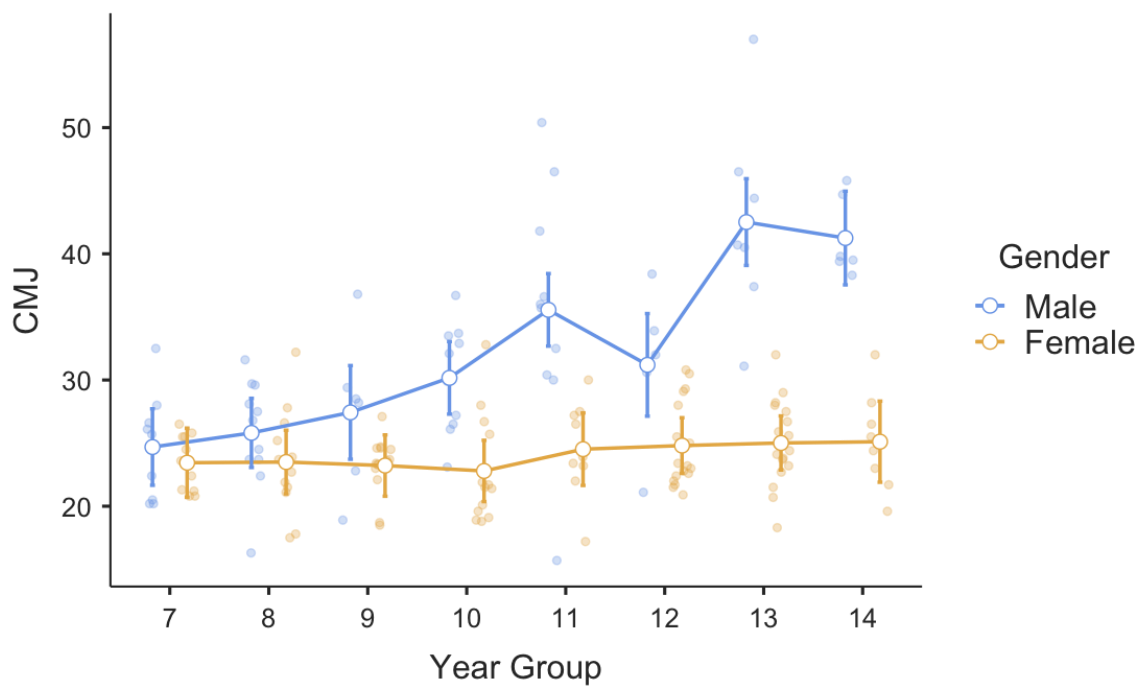


Figure 4-5. Male and female CMJ observed and estimated mean scores with 95% confidence intervals, split by year group (chronological age)

Table 4-7. CMJ mean difference, standard error and 95% confidence intervals between female and male age groups

Female	Male	Mean Difference	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
12	12	-1.243	1.4638	0.407	-4.318	1.832
	13	-2.364	2.5249	1.000	-10.632	5.905
	14	-3.988	3.0052	1.000	-13.830	5.854
	15	-6.725	2.5872	0.331	-15.198	1.748
	16	-12.117	2.5872	0.000	-20.590	-3.644
	17	-7.755	3.1938	0.513	-18.214	2.705
	18	-19.069	2.8630	0.000	-28.445	-9.693
	19	-17.805	3.0052	0.000	-27.646	-7.963
13	12	-1.189	2.6276	1.000	-9.794	7.416
	13	-2.309	1.6872	0.185	-5.808	1.19
	14	-3.933	2.9907	1.000	-13.728	5.861
	15	-6.670	2.5488	0.316	-15.017	1.677
	16	-12.062	2.5488	0.000	-20.409	-3.715
	17	-7.700	3.1888	0.530	-18.143	2.743
	18	-19.014	2.8408	0.000	-28.318	-9.711
	19	-17.75	2.9907	0.000	-27.544	-7.956
14	12	-1.467	2.3918	1.000	-9.265	6.330
	13	-2.588	2.2555	1.000	-9.941	4.766
	14	-4.212	1.8356	0.034	-8.069	-0.356
	15	-6.949	2.3178	0.108	-14.505	0.608
	16	-12.341	2.3178	0.000	-19.897	-4.784
	17	-7.979	2.9166	0.225	-17.487	1.530
	18	-19.293	2.5914	0.000	-27.741	-10.844
	19	-18.029	2.7316	0.000	-26.934	-9.123
15	12	-1.896	2.5745	1.000	-10.314	6.522
	13	-3.016	2.4279	1.000	-10.955	4.922
	14	-4.640	2.9403	1.000	-14.254	4.973
	15	-7.377	1.7322	0.000	-10.969	-3.785
	16	-12.769	2.4950	0.000	-20.927	-4.611
	17	-8.407	3.1394	0.267	-18.672	1.858
	18	-19.721	2.7894	0.000	-28.842	-10.601
	19	-18.457	2.9403	0.000	-28.071	-8.843

Key: Statistical significance ($p < .05$) in bold letters

Table 4-7 (cont). CMJ mean difference, standard error and 95% confidence intervals between female and male age groups

Female	Male	Mean Difference	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
16	12	-0.169	2.2964	1.000	-7.702	7.365
	13	-1.289	2.1838	1.000	-8.453	5.875
	14	-2.913	2.5810	1.000	-11.380	5.554
	15	-5.650	2.2352	0.401	-12.983	1.683
	16	-11.042	3.2558	0.003	-17.882	-4.202
	17	-6.680	2.7375	0.500	-15.661	2.301
	18	-17.994	2.4631	0.000	-26.074	-9.914
	19	-16.730	2.5810	0.000	-25.197	-8.263
17	12	0.117	2.3169	1.000	-7.417	7.651
	13	-1.003	2.1748	1.000	-8.075	6.069
	14	-2.627	2.6688	1.000	-11.306	6.051
	15	-5.364	2.2398	0.543	-12.648	1.920
	16	-10.756	2.2398	0.000	-18.040	-3.472
	17	-6.394	2.1162	0.007	-10.808	-1.98
	18	-17.708	2.5240	0.000	-25.916	-9.501
	19	-16.444	2.6688	0.000	-25.123	-7.765
18	12	0.322	2.1832	1.000	-6.782	7.426
	13	-0.798	2.0466	1.000	-7.457	5.862
	14	-2.422	2.5210	1.000	-10.625	5.781
	15	-5.159	2.1092	0.478	-12.022	1.704
	16	-10.551	2.1092	0.000	-17.414	-3.688
	17	-6.189	2.7034	0.706	-14.986	2.608
	18	-17.503	2.2293	0.000	-22.115	-12.892
	19	-16.239	2.5210	0.000	-24.442	-8.036
19	12	0.424	2.9806	1.000	-9.338	10.185
	13	-0.697	2.8502	1.000	-10.031	8.638
	14	-2.321	3.3128	1.000	-13.170	8.528
	15	-5.058	2.9096	1.000	-14.586	4.471
	16	-10.449	2.9096	0.019	-19.978	-0.921
	17	-6.088	3.4969	1.000	-17.540	5.365
	18	-17.402	3.1747	0.000	-27.799	-7.005
	19	-16.138	1.9469	0.000	-20.379	-11.896

Key: Statistical significance ($p < .05$) in bold letters

4.4.2 Age differences

Anthropometric data for the different age groups are presented in Table 4-2. The range of dance hours for the eight age groups for the duration of the study (19 weeks) was 9,709 hours. Incidence proportion (Table 4-3), clinical incidence (Table 4-4) and injury rates/1000h (Table 4-5) for the corresponding age groups can be seen in the respective tables. Univariate analysis revealed non statistically significant difference between the age groups for male ($F(7,60)= 1.16$, $p= .343$) and female ($F(7,103)= 1.86$, $p= .084$) dancers. Female dancers who were ≥ 17 years of age (43% of all females) sustained 35% of the total injuries (Figure 4-6). There was statistically significant interaction between the effects of age and gender in the CMJ scores ($F(7,153)= 8.24$, $p< .001$, $\eta_p^2= .274$). Statistically significant differences in the CMJ scores were observed between the age groups ($F(7,153)= 12.61$, $p< .001$, $\eta_p^2= .366$). Statistically significant differences were revealed between the age groups for the male dancers ($F(7,56)= 9.31$, $p< .001$, $\eta_p^2= .538$), but not for the female dancers ($F(7,97)= .965$, $p< .461$, $\eta_p^2=.65$) (Table 4-8). Pairwise comparisons revealed statistically significant differences for males between the younger and older dancers, for details (mean difference and 95% confidence intervals) please see Table 4-9.

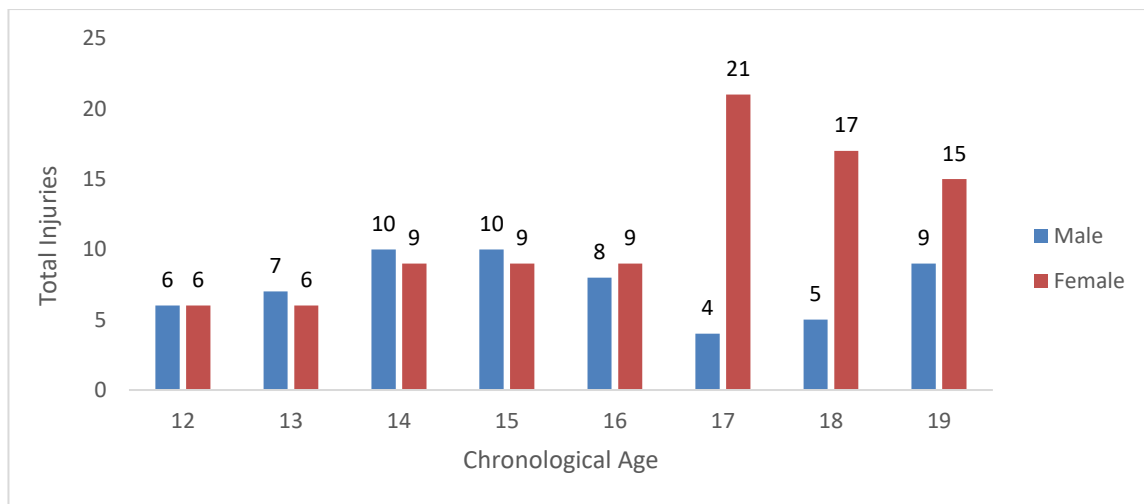


Figure 4-6. Total number of injuries in the different age groups for males and females

Table 4-8. CMJ mean difference, standard error and 95% confidence intervals between all female age groups

Age	Comparison Age Groups	Mean Difference	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
12	13	-.055	1.3857	1.000	-4.506	4.397
	14	.224	1.3628	1.000	-4.154	4.602
	15	.653	1.3628	1.000	-3.726	5.031
	16	-1.075	1.4779	1.000	-5.822	3.673
	17	-1.360	1.3088	1.000	-5.565	2.844
	18	-1.566	1.2945	1.000	-5.724	2.593
	19	-1.667	1.5717	1.000	-6.716	3.382
13	14	.279	1.3028	1.000	-3.907	4.464
	15	.707	1.3028	1.000	-3.478	4.892
	16	-1.020	1.4227	1.000	-5.591	3.551
	17	-1.306	1.2462	1.000	-5.309	2.698
	18	-1.511	1.2311	1.000	-5.466	2.444
	19	-1.612	1.5199	1.000	-6.495	3.270
14	15	.429	1.2784	1.000	-3.679	4.536
	16	-1.299	1.4005	1.000	-5.798	3.201
	17	-1.584	1.2207	1.000	-5.506	2.337
	18	-1.790	1.2053	1.000	-5.662	2.083
	19	-1.891	1.4991	1.000	-6.707	2.925
15	16	-1.727	1.4005	1.000	-6.226	2.772
	17	-2.013	1.2207	1.000	-5.935	1.909
	18	-2.218	1.2053	1.000	-6.090	1.654
	19	-2.320	1.4991	1.000	-7.136	2.496
16	17	-.286	1.3480	1.000	-4.616	4.045
	18	-.491	1.3341	1.000	-4.777	3.795
	19	-.593	1.6044	1.000	-5.747	4.562
17	18	-.205	1.1439	1.000	-3.880	3.470
	19	-.307	1.4502	1.000	-4.966	4.352
18	19	-.101	1.4373	1.000	-4.719	4.516

Table 4-9. CMJ mean difference, standard error and 95% confidence intervals between male age groups.

Age	Comparison Age Groups	Mean Difference	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
12	13	-1.120	2.7695	1.000	-10.206	7.965
	14	-2.744	3.2475	1.000	-13.398	7.909
	15	-5.481	2.8311	1.000	-14.769	3.807
	16	-10.873	2.8311	.009	-20.161	-1.585
	17	-6.511	3.4369	1.000	-17.786	4.764
	18	-17.825	3.1052	.000	-28.012	-7.638
	19	-16.561	3.2475	.000	-27.215	-5.907
13	14	-1.624	3.1272	1.000	-11.883	8.635
	15	-4.361	2.6923	1.000	-13.193	4.471
	16	-9.753	2.6923	.018	-18.585	-.921
	17	-5.391	3.3234	1.000	-16.294	5.512
	18	-16.705	2.9792	.000	-26.479	-6.932
	19	-15.441	3.1272	.000	-25.700	-5.182
14	15	-2.737	3.1819	1.000	-13.175	7.702
	16	-8.129	3.1819	.375	-18.567	2.310
	17	-3.767	3.7311	1.000	-16.007	8.474
	18	-15.081	3.4281	.001	-26.327	-3.835
	19	-13.817	3.5575	.008	-25.487	-2.146
15	16	-5.392	2.7556	1.000	-14.432	3.648
	17	-1.030	3.3749	1.000	-12.102	10.042
	18	-12.344	3.0366	.004	-22.306	-2.383
	19	-11.080	3.1819	.027	-21.519	-.641
16	17	4.362	3.3749	1.000	-6.710	15.434
	18	-6.952	3.0366	.724	-16.914	3.009
	19	-5.688	3.1819	1.000	-16.127	4.751
17	18	-11.314	3.6080	.076	-23.150	.522
	19	-10.050	3.7311	.261	-22.290	2.190
18	19	1.264	3.4281	1.000	-9.982	12.510

Key: Statistical significance ($p < .05$) in bold letters

4.4.3 Maturity status differences

Maturity status classification was available for 166 students, due to the lack of parental height.

The age groups split according to their maturity status are presented in (Table 4-10), whereas the maturity status split by gender can be seen in (Table 4-11).

Table 4-10. Number of students split by chronological age in the different maturity status

Chronological Age	Maturity				
	Pre-Pubertal	Early-Pubertal	Mid-Pubertal	Late-Pubertal	Early-Adulthood
12	19	2	0	0	0
13	8	14	0	0	0
14	0	4	13	0	0
15	0	4	3	13	0
16	0	0	3	14	0
17	0	0	0	20	1
18	0	0	0	11	14
19	0	0	0	0	23
Total	27	24	19	58	38

Table 4-11. Total number of male and female students in the different maturity status

Maturity Status	Gender		Total
	Male	Female	
Pre-Pubertal	14	13	27
Early-Pubertal	14	10	24
Mid-Pubertal	7	12	19
Late-Pubertal	14	44	58
Early-Adulthood	16	22	38
Total	65	101	166

Incidence proportion for the difference maturity status can be seen in Table 4-12 and clinical incidence is presented in Table 4-13. There were no statistically significant differences in injury incidence between the different maturity status ($F(4,161)= 1.65$, $p= .165$, $\eta_p^2 = .039$). No statistically significant differences were observed for the male ($F(4,60)= 1.18$, $p= .329$, $\eta_p^2 = .073$) or female ($F(4,96)= 2.06$, $p= .092$, $\eta_p^2 = 0.79$) dancers. Males in early-pubertal (between 12 to 15yrs) revealed the highest incidence proportion rate (IP= 41.7%, 95% CI: 21.9, 61.4), and the highest clinical incidence (ClinInc= 1.14, 95% CI: -) than all other male groups, whereas, incidence proportion and clinical incidence increased for the females as they were maturing. Moreover, females who were in the late-pubertal (between 15 to 18yrs) and early-adulthood (between 18 to 19yrs) stage sustained 43% of the total injuries (Table 4-13).

Table 4-12. Male and female incidence proportion split by maturity status

Maturity Status	Total Dancers (n)	Injured Dancers (n)	Incidence Proportion (95% CI)	Male		Female	
				Injured Dancers (n)	Incidence Proportion (95% CI)	Injured Dancers (n)	Incidence Proportion (95% CI)
Pre-Pubertal	27	12	44% (26%, 63%)	7	25.9% (9.4%, 42.5%)	5	18.5% (3.9%, 33.2%)
Early-Pubertal	24	14	58% (39%, 78%)	10	41.7% (21.9%, 61.4%)	4	16.7% (1.8%, 31.6%)
Mid-Pubertal	19	12	63% (41%, 85%)	4	21.1% (2.7%, 39.4%)	8	42.1% (19.9%, 64.3%)
Late-Pubertal	58	41	71% (59%, 82%)	11	19% (8.9%, 29.1%)	30	51.7% (38.9%, 64.6%)
Early-Adulthood	38	26	68% (54%, 83%)	10	26.3% (12.3%, 40.3%)	16	42.1% (26.4%, 57.8%)
Total	166	105	63% (56%, 71%)	42	25.3% (18.7%, 31.9%)	63	37.9% (30.6%, 45.3%)

Table 4-13. Clinical incidence for all students split by maturity status

Maturity Status	Total Dancers (n)	Total Injuries (n)	Clinical Incidence (95% CI)	Male			Female		
				Dancers (n)	Injuries (n)	Clinical Incidence (95% CI)	Dancers (n)	Injuries (n)	Clinical Incidence (95% CI)
Pre-Pubertal	27	14	0.52 (-0.46, 1.5)	14	8	0.57 (0.31, 0.83)	13	6	0.46 (0.19, 0.73)
Early-Pubertal	24	20	0.83 (0.1, 1.56)	14	16	1.14 (-)	10	4	0.4 (0.1, 0.7)
Mid-Pubertal	19	14	0.74 (-0.1, 1.6)	7	5	0.71 (0.38, 1.05)	12	9	0.75 (0.51, 1)
Late-Pubertal	58	55	0.95 (0.51, 1.38)	14	12	0.86 (0.67, 1.04)	44	43	0.98 (0.93, 1.02)
Early-Adulthood	38	36	0.95 (0.51, 1.39)	16	13	0.81 (0.62, 1)	22	23	1.04 (-)
Total	166	139	0.84 (0.11, 1.56)	65	54	0.83 (0.74, 0.92)	101	85	0.84 (0.77, 0.91)

There was a statistically significant interaction between maturity status and gender ($F(4,146)=9.42$, $p < .001$, $\eta_p^2 = .205$). Statistically significant differences were also observed in the CMJ between the maturity status groups ($F(4, 146)= 13.289$, $p < .001$, $\eta_p^2 = .267$) and gender ($F(1, 146)= 93.345$, $p < .001$, $\eta_p^2 = .390$) (Figure 4-7). Statistically significant differences were revealed between the male dancers ($F(4,56)= 12.13$, $p < .001$, $\eta_p^2 = .464$). Post hoc pairwise comparisons revealed that Late-Pubertal and Early-Adulthood were jumping higher than the younger dancers, for details see Table 4-15. No statistically significant differences were observed between the females ($F(4,90)= .760$, $p = .554$, $\eta_p^2 = .033$) (Table 4-16). Post hoc pairwise comparisons between females and males revealed that all females had lower jump height scores than males in all the maturity status categories. This difference increased as the females were maturing, for details see Table 4-14.

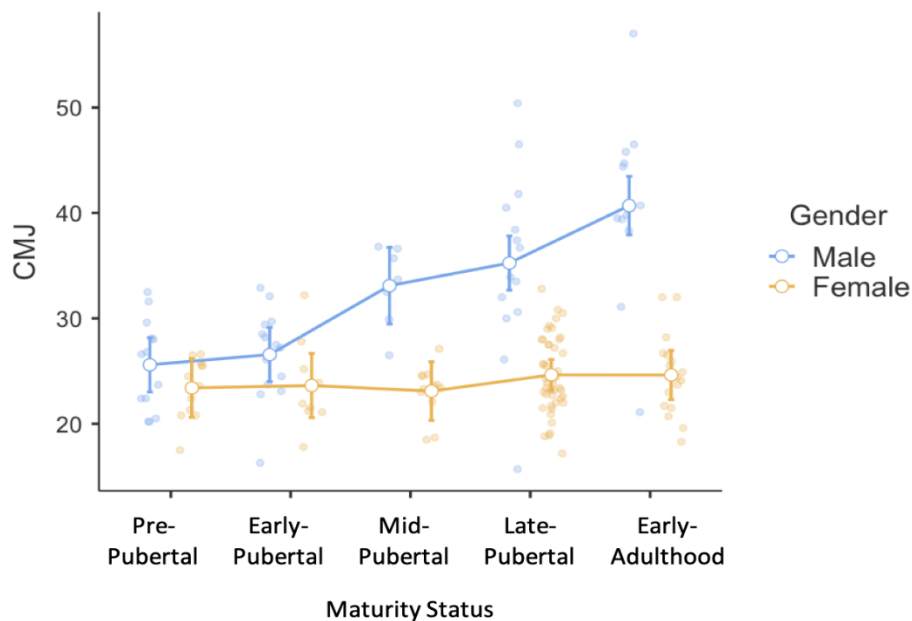


Figure 4-7. Male and female CMJ observed and estimated mean scores with 95% confidence intervals, split by maturity status

Table 4-14. CMJ mean difference, standard error and 95% confidence intervals between female and male maturity status groups

Female	Male	Mean Difference	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Pre-Pubertal	Pre-Pubertal	-2.193	1.4182	.135	-5.1199	.7342
	Early-Pubertal	-3.171	2.5288	1.000	-10.573	4.230
	Mid-Pubertal	-9.700	3.0571	.025	-18.648	-.752
	Late-Pubertal	-11.851	2.5288	.000	-19.253	-4.450
	Early-Adulthood	-17.292	2.6242	.000	-24.973	-9.611
Early-Pubertal	Pre-Pubertal	-1.963	2.7362	1.000	-9.985	6.059
	Early-Pubertal	-2.9414	1.7383	.105	-6.5464	.6635
	Mid-Pubertal	-9.470	3.2567	.053	-19.018	.078
	Late-Pubertal	-11.621	2.7362	.001	-19.643	-3.600
	Early-Adulthood	-17.062	2.8296	.000	-25.357	-8.766
Mid-Pubertal	Pre-Pubertal	-2.493	2.4377	1.000	-9.593	4.607
	Early-Pubertal	-3.471	2.4377	1.000	-10.572	3.629
	Mid-Pubertal	-10.000	1.4233	.000	-13.003	-6.997
	Late-Pubertal	-12.151	2.4377	.000	-19.252	-5.051
	Early-Adulthood	-17.592	2.5297	.000	-24.960	-10.223
Late-Pubertal	Pre-Pubertal	-.950	1.4636	1.000	-5.167	3.267
	Early-Pubertal	-1.928	1.4636	1.000	-6.145	2.289
	Mid-Pubertal	-8.457	1.9409	.000	-14.049	-2.865
	Late-Pubertal	-10.608	1.6082	.000	-13.83	-7.387
	Early-Adulthood	-16.048	1.5534	.000	-20.524	-11.573
Early Adulthood	Pre-Pubertal	-.963	1.9374	1.000	-6.607	4.680
	Early-Pubertal	-1.942	1.9374	1.000	-7.585	3.701
	Mid-Pubertal	-8.471	2.4108	.008	-15.493	-1.449
	Late-Pubertal	-10.622	1.9374	.000	-16.265	-4.979
	Early Adulthood	-16.062	2.3798	.000	-20.945	-11.179

Key: Statistical significance ($p < .05$) in bold letters

Table 4-15. Male CMJ mean difference, standard error and 95% confidence intervals between maturity status

Maturity Category		Mean Difference	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Pre-Pubertal	Early-Pubertal	-979	2.4559	1.000	-8.156	6.199
	Mid-Pubertal	-7.507	3.0078	.155	-16.298	1.283
	Late-Pubertal	-9.659	2.4559	.002	-16.836	-2.481
	Early-Adulthood	-15.099	2.5562	.000	-22.569	-7.628
Early-Pubertal	Mid-Pubertal	-6.529	3.0078	.342	-15.319	2.262
	Late-Pubertal	-8.680	2.4559	.008	-15.857	-1.503
	Early-Adulthood	-14.120	2.5562	.000	-21.591	-6.650
Mid-Pubertal	Late-Pubertal	-2.151	3.0078	1.000	-10.942	6.639
	Early-Adulthood	-7.592	3.0903	.171	-16.623	1.440
Late-Pubertal	Early-Adulthood	-5.440	2.5562	.377	-12.911	2.030

Key: Statistical significance (p<.05) in bold letters

Table 4-16. Female CMJ mean difference, standard error and 95% confidence intervals between maturity status

Maturity Category		Mean Difference	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Pre-Pubertal	Early-Pubertal	-.230	1.4979	1.000	-4.541	4.081
	Mid-Pubertal	.300	1.4282	1.000	-3.810	4.410
	Late-Pubertal	-1.243	1.1393	1.000	-4.522	2.036
	Early-Adulthood	-1.229	1.3190	1.000	-5.025	2.567
Early-Pubertal	Mid-Pubertal	.530	1.4979	1.000	-3.781	4.841
	Late-Pubertal	-1.013	1.2256	1.000	-4.540	2.514
	Early-Adulthood	-.999	1.3942	1.000	-5.012	3.013
Mid-Pubertal	Late-Pubertal	-1.543	1.1393	1.000	-4.822	1.736
	Early-Adulthood	-1.529	1.3190	1.000	-5.325	2.267
Late-Pubertal	Early-Adulthood	.014	.9991	1.000	-2.861	2.889

4.5 Discussion

The aim of this study was to investigate the associations of injury incidence with countermovement jump (CMJ) in pre-professional ballet dancers. In the present study, the probability of a dancer to sustain at least one injury during the period of the investigation was 63.1%, whereas, the probability to sustain two, three or four injuries were 28.3%, 21.9% and 14.3% respectively. The overall injury incidence rate was 1.94/1000h similar to the rates reported for adolescent ballet dancers from a study with similar length (24 weeks) (Bowerman *et al.*, 2014a). Compared to longitudinal studies the results of the present study reveal similar rates with a large cohort study in the U.K. (Ekegren *et al.*, 2014), higher than the rates for Danish adolescent ballet dancers (Leanderson *et al.*, 2011), but lower than the rates for professional ballet dancers (Allen *et al.*, 2012). Bowerman *et al.* and Leanderson *et al.*, however, did not report the confidence intervals of their rates, therefore, the precision of their results needs to be considered with caution. The reported results reveal large width in the confidence intervals, when the group is split by gender or by age. The precision of the estimated incidences and rates of this study, therefore, also needs to be considered with caution.

Male and female dancers reported similar injury rates per 1000 h/dance. The observed incidence rate of injuries was comparable with existing data for these age groups. Specifically, for male dancers (mean age 17) the injury rate per 1000 h/dance was 1.40 (95% CI: 1.19, 1.62) and for females it was 1.36 (95% CI: 1.18, 1.54) (Ekegren *et al.*, 2014), whereas, Bowerman and colleagues observed higher rates for both genders (mean age 16yrs) injury rate per 1000 h/dance was 2.81 and 2.19 for males and females respectively (Bowerman *et al.*, 2014a).

Overuse injuries (73%) accounted for most of the sustained injuries. Overuse has previously been reported to be the main cause of injury in prospective (Luke et al., 2002, Ekegren et al., 2014) and retrospective (Gamboa et al., 2008, Leanderson et al., 2011) studies with pre-professional dancers and professional dancers (Byhring and Bø, 2002, Allen et al., 2012). Consistent with previous studies the most affected region of the body was the lower limb (86%), whereas the most affected body parts were the ankle, knee and foot (Luke et al., 2002, Leanderson et al., 2011, Ekegren et al., 2014). Overuse injuries are considered to be the result of repeated submaximal load with inadequate recovery time (DiFiori et al., 2014). Though it is difficult to pinpoint the reasons behind the observed results, pre-professional dancers expose themselves to high training volume with little variation. This lack of variation, for example in the structure of a ballet class, together with the daily jumping load young dancers are required to perform may contribute to the tissues (i.e. muscles, tendons, bones) inadequate recovery which in turn may contribute to the manifestation of injuries.

No statistically significant differences were found in injury incidence between the chronological age groups. Research has revealed equivocal results on the relationship of age and injuries, as there are studies indicating a positive relationship (Warren et al., 1991, Steinberg et al., 2013), and studies that suggest no association (Kadel, 1992, Steinberg et al., 2014a). Moreover, Caine and colleagues suggest that more months of experience in the pre-professional program to be associated with decreased risk of injuries potentially due to improved skill level, better preventative strategies, selection criteria, or survival of the fittest over time. Their study, however, was based on retrospective data that is characterised by several methodological limitations such as sample selection and size, together with recall bias (Caine et al., 2016). On

the contrary, this study's results indicate that male dancers who were 14 and 15 years of age reported higher injury rates than all other male and female groups; the wide confidence intervals ($p > .05$), however, reduce the precision of the estimation. Also, even though the clinical incidence was two and one injuries per dancer respectively, the injury proportion was not higher than the other groups. One reason for this may be the individual differences (e.g. fitness levels) and response to training combined with the limitations that characterise the calculation of mean values for such a multifactorial, complex, and individual matter such as injury incidence.

In addition, females who were ≥ 17 years of age reported higher injury incidence. This may be related to the increase of the dance hours per week from 17 hrs wk⁻¹ at 16 years old to 27 hrs wk⁻¹ at 17 years old. This study's results, however, are inconsistent, as the incident proportions goes up at the age of 17 and goes down at the age of 19. In high school athletes incidence proportion increases with exposure by hour/week (Rose et al., 2008), specifically, training more than 16 hrs wk⁻¹ is associated with higher injury risk (Rose et al., 2008, Loud et al., 2005). The slight reduction of the incidence proportion in the reported results may be related to the dancers adapting to the high load, or under-reporting injuries in their effort to participate in auditions for potential professional contracts.

There were no statistically significant differences in injury incidence between the different maturity status groups. The period of accelerated growth, i.e. peak height velocity, has been associated with increased risk of injuries (Pediatrics, 2000, DiFiori et al., 2014). Peak height velocity occurs circa 91-92% of adult stature which is around the mid-pubertal maturity stage (Hewett et al., 2015). Contrary to recent studies in youth football (Le Gall et al., 2006, Read et al., 2018a, Johnson et al., 2019), the present study's results do not indicate an association of

injuries with this stage of maturity. Females in the Late-Pubertal and Early-Adulthood maturity status, however, reported higher injury incidence, possibly related to lack of neuromuscular control. It has been suggested that there are differences in the way the neuromuscular system develops in males and females during the pubertal transformation (Myer et al., 2013b). Muscular strength/power and coordination increase with puberty in males, however, this is not observed in females (Beunen, 1988). In particular, females after the adolescent growth-spurt lag in the development of the neuromuscular system which influences their strength and coordination to a greater extent than males (Hewett, 2004). Also, Lee and colleagues suggest that dancers who have sustained an ankle injury have insufficient activation from the foot and hip muscles during landing (Lee et al., 2012), together with proprioception deficits (Lin et al., 2011), therefore, previous injury may be a contributing factor to the present study's results (Allen et al., 2013, Bronner et al., 2018, Ekegren et al., 2014). This, however, is a speculative observation because previous injuries were not accounted for.

The present study revealed no association between injury incidence and CMJ. Angioi and colleagues found a significant negative correlation ($r = -.66$, $p = .004$) between days off dance and standing vertical jump in contemporary dancers (Angioi et al., 2009), however, the coefficient of determination ($r^2 = .43$) explained 43% of the proportion of variance of this relationship (Moita et al., 2017). A recent systematic review (27 studies, $n = 3,209$) suggests that there is moderate evidence that supports the association of lower body power and musculoskeletal injuries risk, however, the exact direction of the association is not clear (de la Motte et al., 2019). Also, since the majority of the injuries that have been reported are related to overuse, both the sensitivity and specificity of a maximal effort test such as the CMJ may be

low. The CMJ, however, is characterised by different phases; it has been suggested that if the landing phase is too stiff, larger peak forces are produced, which may place the dancer at higher risk of sustaining a musculoskeletal injury (McMahon et al., 2018).

The mean scores for the CMJ were statistically significantly higher for the male dancers. All female age groups had lower CMJ scores than all male groups and the jump height difference increased between the older age groups. Gender differences in measures of muscular power such as the maximal jump have been consistently reported in school children (Bovet et al., 2007) and in sports (Maud and Shultz, 1986, Mayhew and Salm, 1990). Interestingly, the CMJ scores of the present study were lower than the scores previously reported for Finnish pre-pubertal (mean \pm SD; 47 \pm .04cm) and pubertal males (mean \pm SD; 53 \pm .04cm) (Pekkarinen et al., 1989) and Danish female adolescent ballet dancers (mean \pm SD; 32.4 \pm 4.6cm) (Claessens et al., 1987). Neither of the studies, however, refer to the type of jump they utilised (free arms or arms akimbo). The use of arms can increase the jump height by 23% in children (Holm et al., 2008), therefore, this factor needs to be taken into consideration when comparing this study's results with other studies.

The reported results indicate different development patterns in jumping for males and females. The CMJ scores for males improved with age and maturation whereas for females they did not. Previous research has shown that the jump height improves with age up to the age of 19 in males but not females (Branta et al., 1984). In line with previous studies the data from the present study show that females, may have reached a plateau after 12 years of age (Doré et al., 2008, Klausen et al., 1989) followed by a decline (Malina et al., 2004). One reason for this may be that athletic performance may not only be induced by training stimulus but also natural

development which depends on maturity status in male adolescents (Meylan et al., 2014). Also, muscle size increases during growth and maturation (Kubo et al., 2001, O'Brien et al., 2010) for males and as a result higher force output may be available during jumping (Radnor et al., 2017). Muscle strength, however, does not only depend on muscle mass but also on the extent to which it is activated, which suggests that there may be other structural and neuromuscular qualities that develop during maturation that may be driving the increased force production (Radnor et al., 2017). Interestingly, this plateau was not present in sub-elite volleyball adolescent female players who have demonstrated improvements from the age groups 12-14 ($\text{CMJ}_{\text{mean} \pm \text{SD}}$; 33.22cm \pm 6.07cm) to the age group 15-17 ($\text{CMJ}_{\text{mean} \pm \text{SD}}$; 37.42 \pm 5.74cm) (Melrose et al., 2007). Volleyball, is a sport where jumping is a fundamental activity and female players may perform approximately 45 jumps in a game (Tillman et al., 2004). Considering the difference in the jumping load between adolescent ballet dancers and adolescent volleyball players, the lack of physiological development in ballet dancers may be related to the nature and focus of training. In vocational dance training the focus is on the development of technical proficiency and an aesthetic look whilst always following the tempo of the music. Research has shown that the intensity of the class is low to moderate (Schantz and Åstrand, 1984, Guidetti et al., 2007) but with potentially higher muscle damage than rehearsals and no cardiorespiratory adaptations (Rodrigues-Krause et al., 2014b). It can be speculated that these limitations restrict physiological adaptations in other physical qualities such as muscular power, simply because the young dancers are never asked to reach for their maximal jump height. In addition, the lack of supplementary training for muscular strength and power during the period of growth

and maturation may also be associated with the observed lack of physical performance development in the female dancers.

Behringer and associates in a meta-analysis (34 studies, $n = 1,432$ participants; 1,019 males) revealed that strength training is effective for the development of motor performance skills such as jumping, in children and adolescents ($d = 0.54$ 95% CI: 0.34, 0.74) (Behringer et al., 2011). In addition, results from another meta-analysis of 14 studies with female athletes (>5,000 participants) suggest that the optimal implementation of neuromuscular training may be during pre- or early adolescence stage of maturity. In particular, during this stage of maturity the risk reduction was 72%, compared with late adolescence (52% risk reduction) (Myer et al., 2013b).

Moreover, Myer and colleagues in a theoretical model of youth development (Figure 4-8) suggest that adolescents who participate in their preferred sport/discipline without any supplementary training reach a lower neuromuscular potential compared to adolescents who are exposed to a training program that incorporates

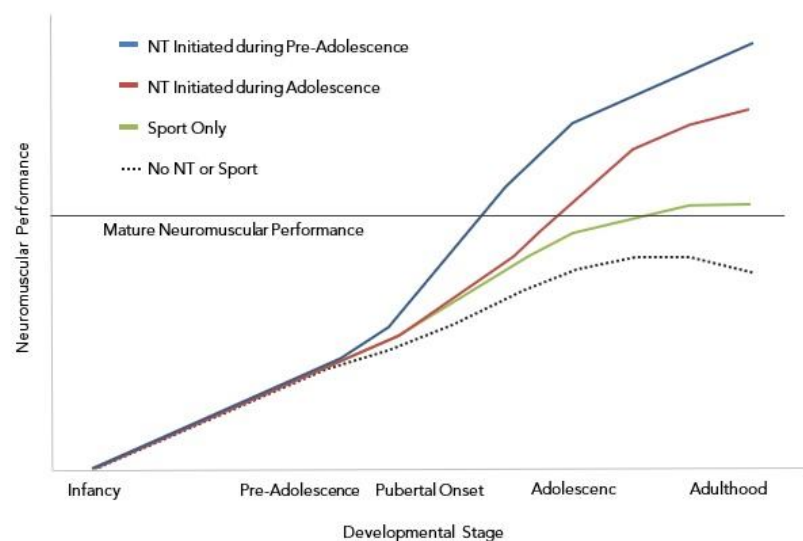


Figure 4-8. Conceptual model which compares the effects of neuromuscular training (NT) initiated at different times in youth. [adapted from Myer et. al (2013)]

general fundamental movements, (e.g. squats, lunges) and exercises that target motor control

deficits, stability exercises, core training, plyometric and agility training at adolescence and pre-adolescent age (Myer et al., 2013a).

The lack of supplementary strength and conditioning training in the dance training curriculum together with the high incidence of injuries and the CMJ scores that have been observed raise the question whether the adolescent ballet dancers may fit the above model due to ballet-only approach in training. It is worth noting, however, that since there is no normative data from the younger (<12yrs old) dancers available in the literature this speculation needs further investigation.

A large proportion of the injuries occurred in September, after the seven-week summer break. Garrick and Requa reported an increase in injuries after holidays in a professional company (Garrick and Requa, 1993). Traditionally young dancers participate in seasonal dance camps, typically lasting approximately one week. It is very difficult, however, to monitor how many camps they do or calculate the number of hours they dance during these camps. It is possible that the young dancers may not do enough to stay active, get detrained and start the new academic year underprepared. Lack of pre-season preparation has also been identified as an injury risk factor in adolescent athletes (Emery et al., 2005, Emery et al., 2007, Bennell et al., 1996, Herman et al., 2012), whereas, pre-season training may reduce injury rates in young athletes (Heidt et al., 2000, Hewett and Myer, 2005).

Due to the high volume of dance training during the academic year, the summer break may be a good opportunity for the dancer to focus on improving muscular strength and general physical fitness under the guidance of a qualified practitioner. Strength and conditioning training

depends on the individual's chronological age, maturity status and experience, therefore, it is advisable for young dancers to train under the guidance of a qualified practitioner (Lloyd et al., 2014a). The integration of neuromuscular training with supervision and correct feedback is integral to the effectiveness of an intervention (Myer et al., 2013b). Neuromuscular training has not been investigated in dance but research from sports indicates that it may be effective against both traumatic (Caraffa et al., 1996, Hewett et al., 1999, Heidt et al., 2000, Myklebust et al., 2003, Olsen et al., 2005, Mandelbaum et al., 2005), and overuse (Olsen et al., 2005, LaBella et al., 2011) injuries, therefore, it is plausible to investigate the effect of this type of training in dancers.

Whilst the relationship of a proportion of the observed injuries with growth and maturation cannot be completely dismissed, a relationship between injuries and the period of accelerated growth was not observed. Considering that this complex biological process cannot be controlled, more attention could be given on more controllable and modifiable injury risk factors. Since most of the injuries are overuse and to the lower limb, if the right measures are taken most of them can be avoided (DiFiori et al., 2014).

It has also been hypothesised that cognitive maturation may be related to the high incidence of overuse injuries in youth. Young athletes may not be able to recognise signs of overuse injuries because they may be unable to cognitively connect vague symptoms, such as fatigue, or poor performance as a sign of injury (Brenner et al., 2007). Interestingly, the reported results indicate more injuries in late-adolescent, and early-adulthood stage of maturation, therefore, the increased injury proportion that has been observed may be related to traits of perfectionism, instead of cognitive immaturity. Perfectionism is “a personality disposition characterised by

striving for flawlessness and setting exceedingly high standards of performance accompanied by tendencies for overly critical evaluations on one's behaviour" (Flett and Hewitt, 2002). It is suggested that perfectionism may play an important role in injury (Williams and Andersen, 1998). A prospective study with 80 junior athletes (65 male and 15 female) revealed that perfectionistic concerns may predisposing athletes to an increased risk of injury (Madigan et al., 2018). This has also been observed in a retrospective study with young gymnasts and dancers (Krasnow et al., 1999), the authors of this study highlight the importance of education in the area of youth injuries and their relationship with psychological traits in order to minimise the potential negative effects on young elite performers.

Lastly, it has previously been suggested that dance teachers and clinicians need to monitor the training loads of the dancers and that dancers need to be educated about the importance of adequate recovery (Ekegren et al., 2014). Even though this is sound advice it might not be an appropriate task for the dance teachers or dancers to do since the schedule is determined by the demands of a set curriculum for the year. Similar to sports, this should be a coordinated multidisciplinary effort between the dance teachers, the medical team and the management of the school, to appropriately periodise training, rehearsals, shows and recovery for the young dancers, with short, medium- and long-term goals clearly defined. This would not only offer more training variability, reduce the strain and monotony for the body and the mind of the young dancer but could potentially decrease the risk of injury. A more dancer-centred approach instead of curriculum-centred approach in the training and development of elite dancers is recommended, whereby growth and maturation are accounted for, the quality and quantity of the load is monitored, and recovery is part of the overall development plan.

4.5.1 Strength and limitations

Injury incidence has been prospectively recorded in elite adolescent pre-professional dancers and the results have been reported according to the Equator Network reporting guidelines, replicating a previous epidemiological study by Ekegren and associates (Ekegren et al., 2014). This is the first study with a large sample to investigate the associations of injuries with a physiological marker (jump height). In addition, this study investigated the relationship of maturity status and injuries. A major limitation of this study, however, is the fact the presented data is from part of the year and not the whole academic year (training season) (Phillips, 2000). This was mainly due to the fact that the physiotherapy company that was providing the school support, changed and new practitioners were employed by the school. This change was unforeseeable and could not have been accounted in advance by the Principal Investigator. In addition, whilst both physiotherapists were very experienced in the field and used standardised methods to record the injuries, there is a possibility of error between the injury recorders. The exact dance exposure for individual dancers could not be calculated, or the time-loss to calculate severity, and previous injury history has not been taken into consideration.

The students were not obliged to see the in-house physiotherapists, therefore, there is a possibility that some injuries may have been missed if a student received treatment from another practitioner. It is unlikely, however, that if a student was not in full-dance capacity that he/she would be unnoticed by either the medical or the artistic staff. Finally, the Khamis-Roche model has not been validated for this population. In addition, the maturity status calculations were conducted based on the self-reported parental height, therefore, the accuracy

of the reported height by the parents may have affected the predictions and needs to be taken into consideration when interpreting the findings of this study.

4.6 Conclusion

The results revealed no association between injury incidence and countermovement jump height. No significant gender differences in injury incidence were observed. Neither chronological age nor maturity status revealed significant associations with injuries, however, more injuries were recorded for the older adolescents as they progress in training. Most of the injuries were of overuse onset and the most affected region of the body was the lower limb. Further research needs to be focused onto strategies and interventions to manage associated injury risk factors that can potentially reduce injury proportion and rates.

5 11+Dance: a neuromuscular injury prevention exercise program for dancers

5.1 Background

Injuries can have a detrimental effect on the dancer's training (Caine et al., 2015). Hamilton and colleagues found that 55% of pre-professional dancers dropped out of training over a period of four years due to injuries (Hamilton et al., 1997). In professional dancers, injuries can have a negative effect on their performance (Allen et al., 2012), and potentially their career (Hamilton et al., 1997). The days off dance in a ballet company ranged between two and ten (Allen et al., 2012). Lastly, the cost of dance related injuries in a professional company are as high as the cost of a college athletic department or a professional sport team (Garrick and Requa, 1993). Garrick and Requa also reported that frequently injured dancers were more likely to have financially devastating injuries. Previous injury has been identified as an injury risk factor in professional (Allen et al., 2012), and pre-professional dancers (Ekegren et al., 2014), therefore, minimising identified risk factors is the plausible thing to do at all levels of performance.

In the epidemiological study presented in chapter 4, the extend of the injury problem was established as the injury surveillance revealed high injury proportion of 63.1% (95% CI: 56%, 70.2%). The risk factors and mechanism of the injuries with the majority of injuries in the lower limb (86%) were also established. The next step, therefore, is to develop preventive measures. In this chapter the current state of the art in injury prevention research in sport and

dance is presented. In addition, the theoretical background of neuromuscular control and training is and the effectiveness of this training to reduce injury incidences and rates is discussed. Finally, the development of the *11+Dance*, an evidence-based injury prevention intervention designed for dancers is presented.

5.2 Current State of the Art

In the past decade, the International Olympic Committee (IOC) in collaboration with 11 research centres (Table 2-2) have developed several programmes that focus on the prevention of injuries and illnesses of elite and recreational athletes. Results from several injury prevention implementation studies reveal that the injury risk reduction can be as much as 50% (Engebretsen et al., 2014). Brunner and colleagues in their umbrella review (24 systematic reviews, $n \approx 250,000$) on the effectiveness of lower extremity injury prevention programmes in team-sport athletes, further support that the utilisation of such programs can reduce injury incidences/rates (Brunner et al., 2019).

In professional ballet and contemporary dance companies, two studies reporting the implementation of a comprehensive injury audit together with a proactive exercise prescription program significantly reduced injury rates with a three, (Allen et al., 2013) and a 15-year (Bronner et al., 2018) program. Allan *et al.* showed a reduction from 4.76 injuries to 2.22 injuries in 1000 hours for males and from 4.14 to 1.81 injuries in 1000 hours for females, whereas Bronner *et al.* indicated a reduction of time-loss injury rate from 0.24 to 0.08 per 1000 hours. Both studies were based on early identification of injuries and individualised exercise

programs, however, no exercise program was reported. Considering the impact an injury may have to a dancer's performance and career (Hamilton et al., 1997, Allen et al., 2012), particularly given the high incidence/prevalence of dance injuries, there is a need to develop and implement interventions to reduce and manage the risks of injuries for dancers.

It has been reported that exercise prevention programs can reduce both acute and overuse injuries in sport, in particular the use of proprioception and strength training (Lauersen et al., 2014, Brunner et al., 2019). Muscular strength deficiencies may be related to poor neuromuscular control which is an associated risk factor for both acute (e.g. anterior cruciate ligament) (Hewett et al., 2006, Hewett and Myer, 2011, Zazulak et al., 2007) and overuse (e.g. patellofemoral pain) (Holmes and Delahunt, 2009, Ireland et al., 2003, Prins and Van der Wurff, 2009) lower limb injuries (Bahr and Holme, 2003, Meeuwisse et al., 2007, Frisch et al., 2009, Myer et al., 2011). Poor lower limb alignment, in particular increased knee valgus during different sport activities such as single leg squat (Crossley et al., 2011) or landing tasks (Myer et al., 2010) has also been associated with patellofemoral pain.

Structured multifaceted injury prevention exercise programs containing neuromuscular strength training (Soomro et al., 2016), and/or proprioception training may significantly reduce injuries (Soomro et al., 2016). The utilisation of a neuromuscular injury prevention program has consistently shown a reduction in the risk of injuries in youth sports by between 30 to 50% (Emery et al., 2007, Emery and Meeuwisse, 2010, Olsen et al., 2005). In dance, similar to sport, biomechanical or technical flaws such as poor external rotation at the hip, foot pronation or poor jumping/landing technique, are being reported as having increased risk for developing

injuries (Poggini et al., 1999), therefore, neuromuscular control to promote correct alignment for dancers would potentially be beneficial.

5.3 Neuromuscular Control

This concept has been discussed in more detail in chapter 2, sub-section 2.8.2

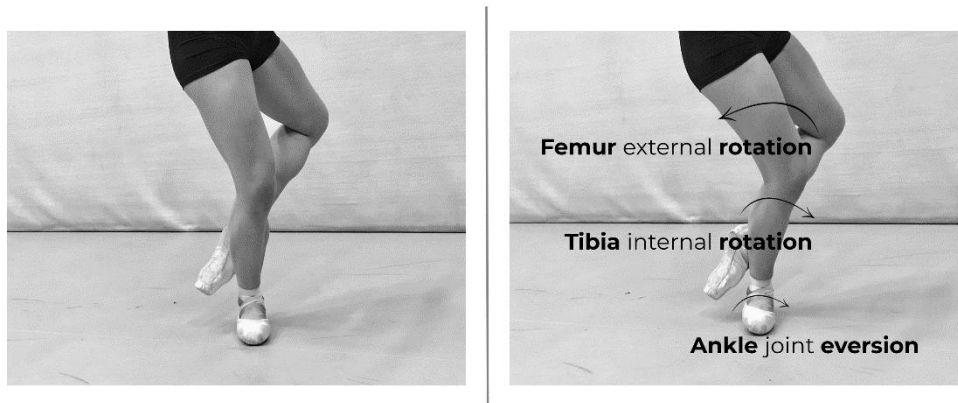
Neuromuscular control, can be defined as the precise recruitment of muscle fibers in the appropriate muscle groups for the production of efficient and coordinated movement (Siff, 2003). Neuromuscular control depends on the correct and accurate functioning of the central and peripheral nervous system (Latash, 2012a, Fort-Vanmeerhaeghe et al., 2016).

The peripheral nervous system can be subdivided into a sensory or afferent division, which detects environmental changes, and the motor or efferent division, that transmits signals away from the central nervous system (Coker, 2017). The integration and analysis of the sensory input, efferent motor commands and resultant movements (Riemann and Lephart, 2002b), create interactions between segments of the body or joints.

This interaction is often referred as coupling, and refers to the notion that the movement of one segment (or joint) can affect the motion of another segment (or joint) (Hamill et al., 2012). Coupling also refers to the relative timing, or synchrony between joints (McClay and Manal, 1997). Deviations from such motions are called “asynchronous” and are thought to have implications for injuries (Hamill et al., 2012). For example, when landing on a single leg (*jetés*) the eversion of the subtalar joint must be followed by internal tibial rotation and external femoral rotation (Figure 5-1).

Experts in the field of neuroscience suggest that the afferent system provides information that is utilised for planning actions but also for correcting ongoing movement in case of inaccuracies

Figure 5-1. Coupling action between the subtalar joint, tibia and femur bones.



Note: On the left, landing from a *jete* with correct alignment and coupling action. On the right, poor neuromuscular control equates to poor alignment of the subtalar, knee and hip joints.

or changes in the environment (Riemann and Lephart, 2002b, Latash, 2012a). Other experts in the field, however, suggest that in explosive sports moves, the forces are too fast for this system to process (Bosch, 2015).

It is suggested that through training, neuromuscular control can be improved (Fort-Vanmeerhaeghe et al., 2016). It has been hypothesised that the development of correct movement efficiency patterns is essential for the safe loading of an injured or deficient body region, by minimising the risk of injury or the creation of compensatory movement patterns (Allen et al., 2013).

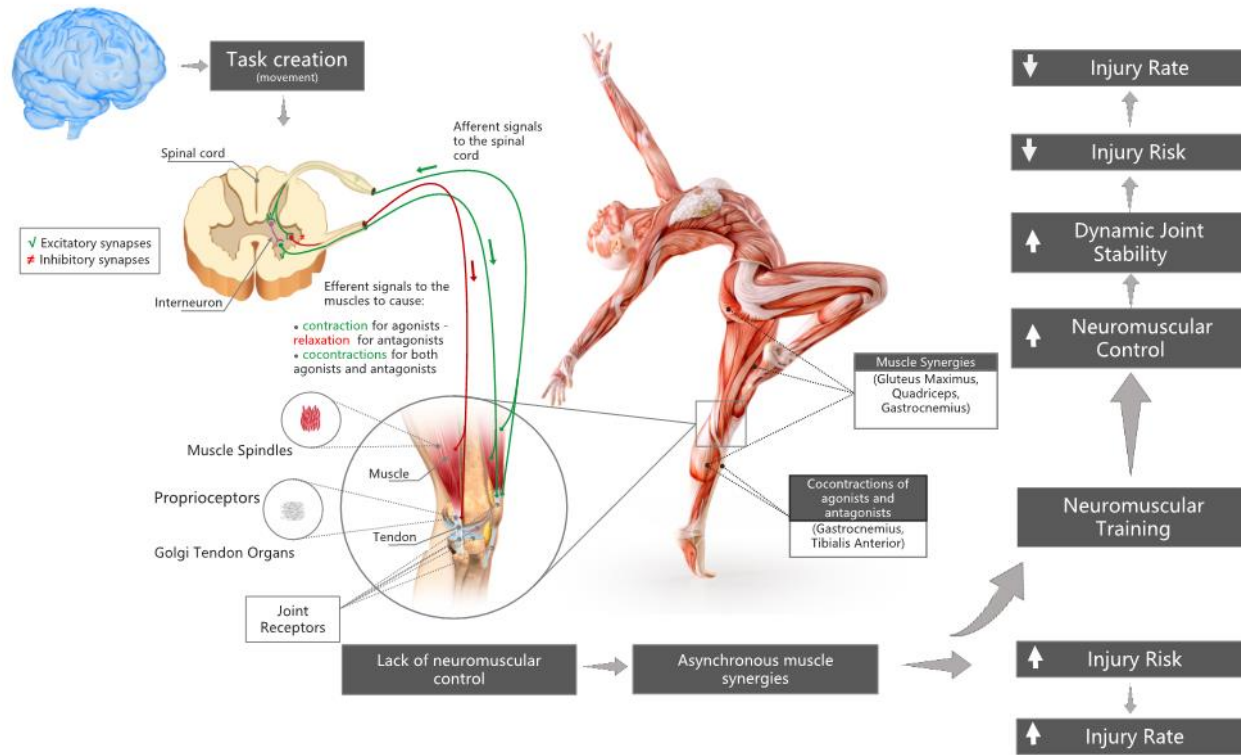
5.4 Neuromuscular Training

Neuromuscular training is an effective method for performance improvement together with the prophylactic effect against injury risks during sports activities (Rössler et al., 2016a, Rössler et al., 2017). Emery and colleagues in a systematic review and meta-analysis that was conducted with 25 studies in youth team sports (e.g. soccer, handball, US football, and basketball) reported a substantial overall protective effect of neuromuscular injury prevention training programmes for the reduction of lower extremity injuries (Emery et al., 2015). Figure 5-2 is a schematic description of the process that takes place in the creation and execution of movement, showing the relationship between movement, the sensorimotor system, the activation of all the receptors (muscle, tendon, joint) for the relevant muscles to contract, relax, or cocontract. Training specifically to improve neuromuscular control can improve dynamic joint control, both of which decrease the risk of injury (Fort-Vanmeerhaeghe et al., 2016).

Research on neuromuscular deficit and its relationship to injuries in dance is limited. Orishimo and colleagues in their study on the landing mechanics of dancers and athletes, suggest that female dancers did not exhibit the same neuromuscular deficits that led to anterior cruciate ligament injuries that are seen in female team sport athletes (Orishimo et al., 2014). Interestingly, lower extremity overuse injuries, and not acute traumatic such as anterior cruciate ligament injuries, are the most common injuries in professional and pre-professional dancers, often associated with repetitive jumping (Bowerman et al., 2015b, Bowerman et al., 2015a, Allen et al., 2012). Anecdotal reports suggest that young elite ballet dancers may perform more than 200 jumps in a regular ballet class every day, with 50% being performed on a single leg. Moreover, compared to sport, there is limited research on injury prevention in dancers (Caine

et al., 2015). One randomized controlled trial that investigated the effect of physical conditioning on musculoskeletal injuries in pre-professional university dancers, indicated less lower back injuries ($p = .02$) and less reported pain ($p = .03$) for the intervention group (Roussel et al., 2014)

Figure 5-2. Relationship between movement, sensorimotor system, muscle activation, joint stability, and neuromuscular control for injury rate reduction in dancers.



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Note: The creation of a task initiates the efferent and afferent actions to occur for the proprioceptors to receive and give feedback about the muscle tension (muscle spindles) and tendon tension (Golgi tendon organs). The joint receptors, located around the joint, provide feedback about joint position, angular speed, and intra-articular tension (Ruffini-ending), joint acceleration (Pacinian corpuscles) and tension around the ligaments (Golgi tendon organ-like endings). The lack of neuromuscular control can affect the muscle synergies which in turn can potentially be the cause of an injury. Neuromuscular training promotes better neuromuscular control and dynamic joint stability which can reduce injury rate.

The lack of research in injury prevention in dance together with the lack of injury prevention interventions suggest a need to develop a neuromuscular training programme for dancers that focuses on lower limb strength and stability together with take-off and landing technique in jumping. Neuromuscular training is generally described as the integration of multi-intervention exercises focusing on balance and proprioception, resistance training, agility (Emery et al., 2015), plyometrics and sports specific exercises (Grindstaff et al., 2006, Hübscher et al., 2010). Although there is no consensus to suggest an optimal neuromuscular training program (Fort-Vanmeerhaeghe et al., 2016), these programs have shown to be effective in decreasing associated risk factors for injury (Wilkerson et al., 2004, Chimera et al., 2004, Lephart et al., 2005, Hewett et al., 2005, Myer et al., 2005, Myer et al., 2006) and injury rates (Caraffa et al., 1996, Hewett et al., 1999, Heidt et al., 2000, Myklebust et al., 2003, Olsen et al., 2005, Mandelbaum et al., 2005, Waldén et al., 2012).

5.5 Intervention Development

Guided from already established injury prevention interventions such as FIFA 11+ (Sadigursky et al., 2017) and FIFA 11+ Kids (Rössler et al., 2017), the 11+Dance was developed. The intervention is an exercise program that was developed based on the findings of previous studies on injury prevalence and characteristics in dancers (Luke et al., 2002, Gamboa et al., 2008, Allen et al., 2013, Bronner et al., 2018), according to the Translating Research into Injury Prevention Practice (TRIPP) framework (Figure 5-3). TRIPP is a framework that consists of six necessary steps in building the evidence base for injury prevention. The first two steps focus on injury surveillance in order to establish the size of the problem, the etiology and the injury

mechanisms (Finch, 2006). For the purposes of this chapter the focus will be on the third stage, which is the development of appropriate preventive measures.

The 11+Dance focuses on muscle activation, muscular endurance in the upper and lower body, together with ankle, knee and hip alignment, balance, and coordination. The workout is split in three phases: 1) activation and local muscular endurance, 2) balance and coordination and 3) bilateral and unilateral take-off and landing technique.

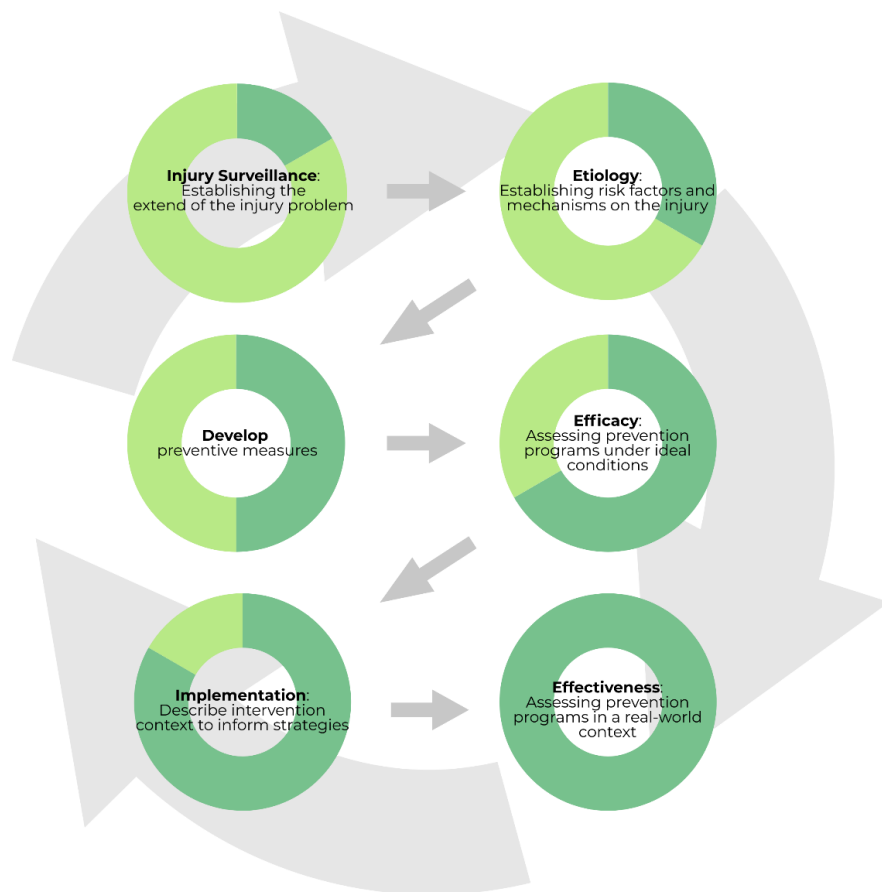


Figure 5-3. The Translating Research into Injury Prevention Practice (TRIIPP) framework for research leading the real-world dance injury prevention (adapted from Finch, 2006).

The pool of the selected exercises used are split into two sessions which can be alternated to minimise the risk of motivation loss through training monotony (Rössler et al., 2016a). The structure of the program is based on the concept of Raise-Activate-Mobilize-Potentiate (Jeffreys, 2006). Raise stands for the elevation of body temperature, heart and respiration rate, blood flow, and joint fluid viscosity through low intensity activities. The Activate and Mobilize phase has the focus to activate key muscle groups and mobilize key joints for the activity; lastly Potentiation means to improve the effectiveness. In sport the potentiation phase would involve a gradual shift towards the actual sport performance (e.g. basketball lay-up or sprinting in football), however, due to the constraints of the dance class structure, potentiation is focused on preparing the musculotendinous complex for take-off and landing. For more details of the 11+Dance structure and exercises please see Table 5-1.

In the 11+Dance the *raise* phase involves rope skipping. This low intensity activity also focuses on the conditioning of the ankle joint and its surrounding tissues (Miyaguchi et al., 2014). The workout then proceeds to the *activate* and *mobilise* phase. Here the focus is on activation of the lumbopelvic hip complex musculature, and quadriceps and hamstrings, together with mobilisation of key joints (ankle, knee, hip). Variations of planks and bridges as well as mini-band walks, together with active stretching exercises like bodyweight squats and lunges variations are utilised. This is followed with phase-2 where the aim is balance and proprioception with single-leg exercise variations with rotation by the hip in all planes (sagittal, frontal and transverse), together with light ballistic stretching whilst standing on single-leg are used to challenge and improve these qualities. The workout concludes with *potentiation*

exercises in the form of light intensity bilateral and unilateral take-off and landing technique exercises.

The difficulty of each exercise is progressively increased in four levels. A dancer can progress to a more difficult level once he/she can consistently perform an exercise accurately with special attention on the body alignment, stability and overall quality and flow of movement. At level 1 the *plank* is performed with three points of contact (leg raise), at level 2 the length of the hold is increased from 10 to 15 seconds, at level 3 the same exercise is performed with two points of contact (raise leg and the opposite arm) and finally at level 4 the exercise progresses to three points of contact with rotation. Special attention is given to the ability of the dancer to remain centred, keep his/her spine in a neutral position and scapula control. When performing the bridge and the hamstring raises, the end position is reached when the knees, hips and shoulders are aligned. The same exercises can be progressed in a single-leg action, with the dancer remaining centred and the pelvis in a neutral position throughout the movement. The key point for these exercises is the development of endurance without inducing fatigue, therefore, the practitioner/teacher is advised to regress or reduce the load of the exercise (time, or repetitions) as they think it is appropriate.

The bodyweight level 1 *squat to relevè* is performed with a slow eccentric phase at level 2, with a pause at the bottom position at level 3 and with a single leg relevè in the level 4. Lunges begin with flat feet on the ground, then progress to *demi-pointé*, then demi-pointe and *développé devant* and then lunge with rotation. It is important for the dancer to rise to the demi-pointe position he/she can control, avoiding ankle movement in the frontal plane (left of right) to promote the creation of correct neuromuscular control. Balance exercises are progressed closing

the eyes so that the dancer cannot rely on his/her vision and then by raising the heel to demi-pointe. In the “hip-airplane” exercise the dancer is required to flex by the hip whilst keeping the spine and the hip of the non-standing leg in a neutral position and then rotate in the transverse plane until the shoulder and the hip of the non-standing leg are perpendicular to the ground. The cue for this exercise is “move the hip bone and the shoulder bone together”. The level of difficulty either changes by the increase of the angle of the flexion ($\approx 90^\circ$) and/or by the speed of the movement.

Table 5-1. 11+Dance exercises, sets, repetitions and progressions

		Sets	Duration	Reps	Exercise			
Skipping	Week 1-3	3	1min		Two legs			
	Week 4-5	3	1min		Alternate Single leg			
	Week 6	4	1min		Alternate Single leg			
	Week 7-8	5	1min		Alternate Single leg			
	Week 9	1	3min		Travelling skips			
	Session 1			Level 1	Level 2	Level 3	Level 4	
Phase 1	1	1	10-15 sec	2 e/s	Plank on elbows - raise the leg	Increase time of hold	Raise opposites	Rotate
	2	1		2 e/s	Plank on hands - raise the leg	Increase time of hold	Raise opposites	Rotate
	3	1		2 e/s	Side Plank - on knee	On elbow and side of foot	On hand and side of foot	Elbow to knee
	4	1		10 e/s	SL Bridge & Hold	Increase time of hold (3-5sec) Increase reps to 12-15/Distance	Increase sets to 2	
	5	1		8-10	Hamstring Raises		Single Leg	Increase speed
	6	1-2		10	Squats to releve	Slow Eccentric Phase	Pause at the bottom Demi-Pointe Developpe front to	Finish on one leg- alternate
	7	1-2		8 e/s	Walking Lunges	Demi-Pointe to lunge	Lunge	Lunge and Rotate
	8	1		8 e/s	Side Lunges	Increase reps to 12	Side to cross body	
Phase 2	9	1		10 e/s	SL Balance - Hip rotation	Increase speed	Closed eyes	Demi-Pointe
	10	1		10 e/s	SL Balance - Upper body rotation			
	11	1		10 e/s	Cross-Country Skiing	Increase sets to 2	With overhead extension	Use light weight
	12	1		5-10 e/s	Hip Airplane	Increase height of the leg	Increase speed of movement	Closed eyes
Phase 3	13	1-2		10	Forward landings	Put the brakes on	1 forward 1 up	
	14	1-2		10	Side landings	Put the brakes on	1 Side 1 up	Rotate
	15	1		8 e/s	SL Forward landings	Put the brakes on	1 forward 1 up	Left - Right - Stick
						Put the brakes on		
	16	1		8 e/s	SL Side landings		1 side 1 up	Step - Cross- Jump

		Sets	Duration	Reps	Exercise			
		Session 2			Level 1	Level 2	Level 3	Level 4
Phase 1	1	2		10 e/s	Plank on hands with elbow taps	Shoulder taps	Raise opposites	Plank on hands with elbow taps
	2	2		10 steps	Bear crawl -Static 3-point of contact	Forward/Backward	Forward/Backward/Side	Bear crawl -Static 3-point of contact
	3	2		10 steps	Crab walk - Static 3-point of contact	Forward/Backward	Forward/Backward/Side	Crab walk - Static 3-point of contact
	4	1		8-10 e/s	Cook Hip lift	Increase sets to 2	Pause at the top	Cook Hip lift
	5	1		10	4-way Monster Walks-straight legs	Increase resistance	Demi-Pointe	4-way Monster Walks-straight legs
	6	1		10	4-way Monster Walks-bend legs			4-way Monster Walks-bend legs
	7	1-2		10	Squats with Overhead Reach	Hold dowel	Squeeze hands against each other	Squats with Overhead Reach
	8	1		8 e/s	Side Slides	Increase reps to 12	Pause at the bottom	Side Slides
Phase 2	9	1		10 e/s	Leg Swings forward	Increase speed	Closed eyes	Leg Swings forward
	10	1		10 e/s	Leg Swings Cross-body			Leg Swings Cross-body
	11	1		12 e/s	SL Reach	Increase sets to 2	Go cross body	SL Reach
Phase 3	12	1-2		10	Forward landings	Put the brakes on	1 forward 1 up	Forward landings
	13	1-2		10	Side landings	Put the brakes on	1 Side 1 up	Side landings
	14	1		8 e/s	SL Forward landings	Put the brakes on	1 forward 1 up	SL Forward landings
	15	1		8 e/s	SL Side landings	Put the brakes on	1 side 1 up	SL Side landings

In the potentiation phase, take-off and landing is focused on the correct alignment, and making the landing as quiet as possible using the cue "*land like a cat*". The skill then progresses to landing with and stopping the descent so that the hips do not go past the knee joint using the cue "*put the brakes on*". Metaphors are utilised as a tool to assist the comprehension of the desired motor skill (Clark and Metcalfe, 2002, Hanin, 2003), in this instance the ability to absorb force. The progression is then to land, quickly rebound upwards and finish with a quiet landing, to promote stimuli for fast recoil in the musculotendinous complex whilst keeping the correct alignment of the ankle, knee, and the hip.

5.6 Discussion

Injuries in dance can cause significant discomfort, distress, disability, reduction of productivity but also substantial costs. Even though preventing or eliminating all injuries is impossible, efforts to reduce them and the associated risks of injuries is warranted (Caine et al., 2015). Injury prevention research is mainly focused on traumatic acute injuries (Brunner et al., 2019), there is however, some evidence that the implementation of such a program can also reduce overuse injuries (LaBella et al., 2011, Olsen et al., 2005).

Petushek and colleagues in a recent systematic review and meta-analysis (18 studies, n= 27,231 participants) on evidence-based best-practice guidelines for the prevention of injuries suggest that the effectiveness of an intervention could potentially be assessed via a meta-analytic driven checklist with a maximum score of 11 points. The authors suggest that the following factors need to be considered: the inclusion of exercises such as 1) lunges, 2) hamstring exercises, 3)

heel/calf raises, 4) the inclusion of up to five landing stabilisation exercises, 5) the age of the participants (adolescents or adults), 6) the length of time the participants engage with the intervention in the year (pre-season only or all through the year), and 7) whether the coach/teacher has been trained or educated on the injury prevention program (Petushek et al., 2018). The 11+Dance workout is a 20-30 minute neuromuscular-based workout that scores ten out of 11 points in the best-practice checklist, indicating that its utilisation may potentially have a large benefit.

The effects of this intervention on physiological parameters together with the frequency (times per week) that it needs to be performed are under investigation, however, there is some evidence of acute effects on the landing technique of young athletes after one session of an injury prevention program (Root et al., 2015).

5.7 Conclusion

This is the first neuromuscular workout specifically developed for dancers. The 11+Dance fills a gap in the literature, as it is an evidence-based training program with the aim to promote ankle, knee, hip stability, local muscular endurance, take-off and landing technique. Considering the high prevalence of injuries reported in the different genres of dance, implementing an injury management strategy that includes an injury prevention program is both the plausible and ethical action to take for all levels of performance. Longitudinal studies with larger cohorts are essential in order to assess the true effects of such intervention on injury type, incidence, and severity in dance.

6 Neuromuscular training in adolescent pre-professional ballet dancers: a feasibility randomised controlled trial

6.1 Background

In line with the available literature the epidemiological report presented in chapter 4 has revealed high injury proportion (63%) and most injuries were reported as gradual onset or overuse (73%). The highest percentage of injuries were sustained on the lower limb (86%), with the ankle (33%), knee (18%), and the foot (17%) being the most affected areas. The investigation of an injury prevention intervention proves to be paramount.

Structured multifaceted injury prevention exercise programs containing neuromuscular strength training (Soomro et al., 2016), and/or proprioception training may significantly reduce injuries (Soomro et al., 2016). The utilisation of a neuromuscular injury prevention program has consistently shown a reduction in the risk of injuries in youth sports by between 30 to 50% (Emery et al., 2007, Emery and Meeuwisse, 2010, Olsen et al., 2005). Surprisingly, research in injury prevention interventions in dance is scarce (Caine et al., 2015). A limited number of quasi-experimental, i.e. non-randomised and without a control group studies (Mistiaen et al., 2012, Roussel et al., 2014) or studies that used previous cohort data (Allen et al., 2013, Bronner et al., 2018) suggest that the utilisation of proactive exercise programs and general strength and conditioning training interventions may be associated with the reduction of injury incidence. The research design, however, i.e. lack of randomisation, lack of control group, or the use of past data, is the main reason one cannot be certain that the positive changes that have been observed are not dependent to confounding factors (i.e. time, selection bias) other than the interventions in place (Emery, 2010). Arguably, the strongest form of evidence for the

evaluation of an injury prevention intervention is a randomised controlled trial (Friedman et al., 2010), however, this may not always be possible in a professional dance company setting, due to potential adverse or beneficial effects of any new intervention.

The lack of research on injury prevention in dance raises the question of the feasibility of a randomised controlled trial in the vocational setting. Feasibility studies are an important preparatory step for future

definitive studies (Eldridge et al., 2016). Eldridge and colleagues developed a conceptual framework (Figure 6-1) for the design of clinical trials, where they indicate that when there is uncertainty about the feasibility of randomised controlled trials, a feasibility study is necessary (Eldridge et al., 2016).

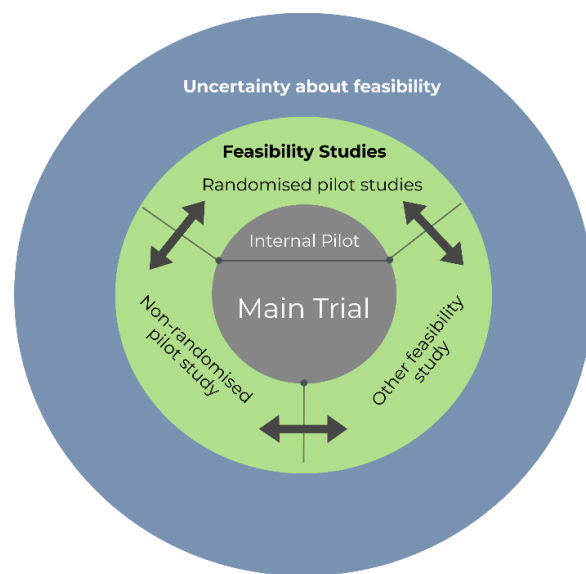


Figure 6-1. Conceptual framework for the design of clinical trials

[adopted from Eldridge et al. (2016)]

6.2 Aims

The aim of this study, therefore,

was to assess the feasibility of a randomised controlled trial for the utilisation of neuromuscular training in elite adolescent ballet dancers. The specific objectives were to examine the intervention adherence and fidelity (Whitehead et al., 2014).

6.3 Methods

Study details are presented according to the CONSORT guidelines (Moher et al., 2010).

6.3.1 Trial design

A balanced randomisation [1:1], parallel-group, controlled study design was used to address the aims of this study. The study was conducted in a vocational ballet school with elite adolescent dancers in Birmingham, United Kingdom.

6.3.2 Outcomes

The primary outcome of this exploratory analysis was to assess intervention adherence and fidelity. The secondary outcomes were the length and organisation of the assessment of the physiological parameters CMJ, RSI, IMTP. Exposure (adherence) was measured through the attendance records that were updated daily for the intervention group and interviews with the individuals who missed sessions were conducted by the PI to identify the reasons for their absence. Exposure was defined as the percentage of total sessions participation. Participants who reported an injury were assessed by the physiotherapist. During half-term break, the participants were asked to report if they performed the workout and how many times.

6.3.3 Participants

Twenty-two elite adolescent ballet dancers volunteered to participate in this study. All participants had to be cleared by the medical centre of the school in order to take part in the study. The participants were all exposed to same amount of dance hours per week ($n = 27 \text{ hrs wk}^{-1}$).

6.3.4 Randomisation

Participants were randomly assigned to either the intervention or the control group via a number-generator software (Microsoft Excel) and by an independent blinded researcher. The ballet teachers, the participants, and the principal investigator (PI) could not have foreseen the group selection.

6.3.5 Procedures

Anthropometric data was collected at baseline. Standing height was measured barefoot to the millimetre (0.1 cm) with a portable stadiometer (SECA 213) and weight measurements to the closest gram (0.1 kg) with a wireless column scale (SECA 704s) were obtained before breakfast and with minimum clothing. BMI (kg/m^2) was then calculated (mass in kg divided by height in m squared) (Keys et al., 1972).

Before participation in this study the participants' parents/guardians were informed through a written description of the study and a request for consent to allow their children to participate in the study. The school also provided the lead researcher with a *loco parentis* authorisation for the students to participate in the study and finally the participants signed a *willingness to participate* form. Ethical approval was attained from the University of Wolverhampton ethics committee.

Baseline data were collected by the PI whereas post-test data were collected by a blinded independent assessor. Any participant who reported an injury before the randomisation was excluded from the group selections, whereas if any participant reported an injury and could not

participate fully in the testing protocol, after the randomisation he/she was excluded from the analysis.

As reported in previous studies, the testing took place in a thermoregulated room (temperature 19°C) and on the same floor (rubber floor) (Rössler et al., 2016a). Testing for both groups commenced with a warm-up comprising of two minutes light cardiovascular exercise followed by dynamic stretches targeting the big muscles of the lower body (Flanagan et al., 2008). All participants were familiar with the tests as they were routinely used in order to monitor their fitness (Cloak et al., 2014).

6.3.6 Equipment

Jump height and the reactive strength index (RSI) were measured with an Optojump Next system (Microgate, Version 1.10.19). The Optojump is a photocell system that consists of two bars, a transmitting and receiving one that are one metre long and are equipped with 33 optical light-emitting diodes (LEDs). The transmitting leds are continuously communicating with the corresponding receiving leds. The LEDs are positioned at 0.3cm from the ground and at 3.125cm interval on the bar. Flight time is calculated through the break of them beam that switches on and off the chronometer on the computer (manufacturer's declared accuracy: $1 \times 1000 \text{ s}^{-1}$) (Castagna and Castellini, 2013, Castagna et al., 2013). The Optojump Next has demonstrated excellent validity and reliability scores, ICC range 0.997-0.998 and 0.982-0.989 respectively (Glatthorn et al., 2011). Isometric lower body strength was measured through Powerlab (Ad Instruments, UK). Powerlab has been reported to have high validity and reliability scores, ICC ranges 0.94-0.99 and 0.90-0.99 respectively. Powerlab was calibrated using kilogram weights before use (Papadopoulos and Stasinopoulos, 2016).

6.3.7 Jumps

The participants performed three countermovement jumps (CMJ) bilaterally, three CMJs unilaterally and three drop jumps (DJ) from a 30 cm box in a non-fatigued state (Flanagan et al., 2008). The Optojump Next measured the flight time (FT) for the CMJ and automatically calculated the JH.

The highest CMJs were used for analysis (Castagna and Castellini, 2013). The Optojump Next also calculated the contract time (CT) and the FT for the DJ. From this measurement the RSI was then calculated using the equation (McClymont, 2003):

$$RSI = JH(m) \div CT(s)$$

Each participant had a 30 second recovery between CMJs (DiStefano et al., 2010), and 60 second recovery between the DJs (Ayala et al., 2017b). The average flight and contact time from the three jumps was then used for the analysis (Ayala et al., 2017b). To avoid any potential cushioning effect from the footwear (Pickering Rodriguez et al., 2017), and to replicate the most common conditions the young dancers dance in, all jumps were performed barefoot. For the CMJ the participants were instructed to stand upright, with their feet hip width apart, and keep their hands akimbo throughout the jump, to restrict upper body interference (Lees et al., 2004, Hara et al., 2006, Hara et al., 2008). To begin the test, the participants performed a squat to a self-selected depth followed by a fast upward vertical movement, triple extending at the hips, knees and ankles with an explosive intent to jump as high as possible (Bishop et al., 2018). The participants were also instructed to remain with the knees and ankles extended and land in the same position and location in order to avoid horizontal displacement which could

have an effect on flight time (Chaouachi et al., 2017). If the participants deviated from the instructions, they had to re-take the jump

after a 60-second rest period (Bishop et al., 2018). Instructions for the CMJ included, *keep the flow of your movement, jump as fast and as high as you can, by pushing the earth away.*

For the DJ (Figure 6-2) the instructions included, to initiate the move by stepping from the box and drop without pushing with the

standing leg, whilst keeping their hands akimbo during the jump, touch the ground with both feet at the same time, and then immediately jump as high as possible (Earl et al., 2007). The verbal cues that were given were: *the floor is really hot, once you touch the ground jump as high as you can, as fast as you*



Figure 6-2. Drop jump from a 30cm box

can. In order to limit performance

variability, if the contact time was ≥ 0.3 milliseconds the jump was discarded and the participant performed it again after the prescribed rest time (Healy et al., 2017).

6.3.8 Isometric Strength

A three second isometric mid-thigh pull (IMTP) was used as the measure of lower body strength. Participants stood on a custom-made platform where a load cell (LCM Systems Ltd, UK) was anchored and the signal was processed by Powerlab (AD Instruments, UK). On the other end of the load cell there was a chain and at the end of the chain a small bar that was

placed at mid-thigh. They were asked to assume the position by self-selecting their hip and knee angles (Wang et al., 2016) whilst following the instructions, to place the chain between your feet, and their feet underneath their hips, to keep their knees soft, their back flat (neutral) and upright, and their chest out. They were then given the following instruction: *pull the bar with straight arms and push the platform away with your legs whilst maintaining your posture*. The participants were instructed to relax before the command “Pull!” to avoid the precontraction (Wang et al., 2016). The pull lasted for three seconds, for three consecutive times with five seconds rest between the pulls, and the peak force (N) was then recorded and was used for the analysis. Due to the fact that the IMTP test was conducted with an in-house rig a between-session reliability test was conducted to ensure that there was no familiarisation effect.

6.3.8.1 Between-session reliability test for the isometric mid-thigh pull (IMTP)

A between-session reliability assessment was conducted ($n = 35$, male = 18, mean \pm SD age = 14 \pm 1.7yrs). The study employed a within-subjects repeated measures research design, whereby the isometric mid-thigh pull was assessed twice on the same day with 3 hours difference between each assessment. All the participants were familiar with the test as it was used regularly as part of their muscular strength assessment. The details of the protocol are described in section 6.3.8.

Each participant was provided two warm-up pulls, one at 50% and one at 75% of the participant's perceived maximum effort, separated by 1 minute of rest. Once the warm-up pulls were completed the participants were given a countdown of “3, 2, 1, Pull”. To ensure there was no slack between the participant's body, the bar and chain before the start of the pull minimum pretention was allowed (Thomas et al., 2017). The highest score from both sessions was used

for the analysis. The analysis was conducted using a spreadsheet designed by W. Hopkins (Hopkins, 2000). The intraclass correlation coefficient (ICC), coefficient of variation (CV), the smallest effect from observed standard deviation (SD) and 90% confidence intervals (90% CI) are reported (Brady et al., 2020).

The results from the reliability test revealed very high intraclass correlation, ICC= 0.95 (90% CI: 0.91, 0.97), and an acceptable CV= 7.2% (90% CI: 6.0, 9.1). The smallest effect from observed SD was equal to 6.3% (90% CI: 5.2, 7.9).

6.3.9 Intervention

The workout is an adapted version of the FIFA 11+ workout. The FIFA 11+ is a neuromuscular workout that lasts approximately 20-30 minutes, consisting of 15 exercises. It was developed by the Federation Internationale de Football Association (FIFA) Medical Assessment and Research Centre (Soligard et al., 2008). It consists of dynamic exercises selected for injury prevention based on scientific evidence and best practice (Bizzini et al., 2013). The exercises are grouped into three parts, parts 1 and 3 include running exercises combined with active stretching, controlled partner contacts, planting and cutting movements. Part 2 incorporates strength, agility and balance conditioning exercises. Due to the fact that this workout was created specifically for football (Soligard et al., 2008), running exercises, controlled partner contacts, planting and cutting movements were dropped, in order to make it more applicable to dance. The focus was more on the muscle activation, local muscular endurance, ankle, knee, hip alignment, balance and coordination. The workout was split in three parts, Part 1: activation and local muscular endurance, Part 2: balance and coordination and Part 3: unilateral and bilateral take-off and landing technique. The pool of the selected exercises used in the

workout were split into two sessions (1 and 2) which they were alternated daily to minimise the risk of motivation loss through training monotony (Rössler et al., 2016a, Anderson et al., 2003).

The participants from the intervention group were asked to take part in the workout before the ballet class five days per week. The intervention group was asked not to discuss the workout with the control group.

6.3.10 Control

The participants in the control group were asked not to be present in the studio while the intervention group was doing the intervention workout in order to avoid trial contamination by exposing the control group to the intervention. The control group was not given any instructions as to what to do before the ballet class.

6.3.11 Statistical analysis

Intervention fidelity, and the participants' feedback was recorded and analysed through a spreadsheet (Microsoft Excel).

6.4 Results

6.4.1 Feasibility of the intervention

Out of the possible 45 sessions the average intervention adherence was $43 \pm 9\%$. One participant took part in 49% of the sessions (n= 22 sessions), five took part in 47% (n= 21 sessions), two took part in 44% (n=20 sessions), one in 40% (n=18 sessions) and one in 16% (n= 7 sessions).

Weeks one to three of the intervention had the highest participation (90% of all participants) performed 12 sessions out of the possible 15. Weeks four and five were half-term break, therefore, there was no supervised training. None of the participants reported to have performed the intervention during the half-term break. From week six to week ten, the maximum number sessions the participants took part were three and the minimum was one per week. None of the participants reported that have performed any of the exercises during the half-term break. There was no protocol violation from the control group.

6.4.2 Feasibility of the outcome measures

Attendance for the pre and post testing was low 45% and 36% for the intervention and control group, respectively. The tests took approximately ten minutes per participant. When grouped in groups of three, total time including the warm-up was approximately 15 minutes. The participants did not regard the assessments as time consuming, however, there were participants who got lost in the follow-up (for details see trial flowchart Figure 6-3).

6.4.3 Study and intervention length

The study lasted for ten weeks from September 2016 to November 2016. The workout lasted minimum 20 min and maximum 30 minutes.

6.4.4 Adverse effects

The main complaint that was reported by most of the participants (>90%) was muscle soreness and the feeling of having *heavy legs* at the beginning of the ballet class (*barre*). This feeling faded away after the first two weeks but was reported again after the two weeks half-term break.

Four of the female participants (50%) expressed fear of muscle size increase and were reluctant to continue after the half term. Fatigue was also reported as a reason for the attrition.

6.4.5 Participant characteristics at baseline

Baseline characteristics of the 22 participants (mean \pm SD, age= 16.6 \pm .52 years; weight= 54.9 \pm 8.94 kg; height= 170 \pm 8.0 cm; BMI= 18.7 \pm 1.6 kg \cdot m²) are presented in Table 6-1 and the flowchart of the trial is presented in Figure 6-3.

Figure 6-3. Trial flowchart

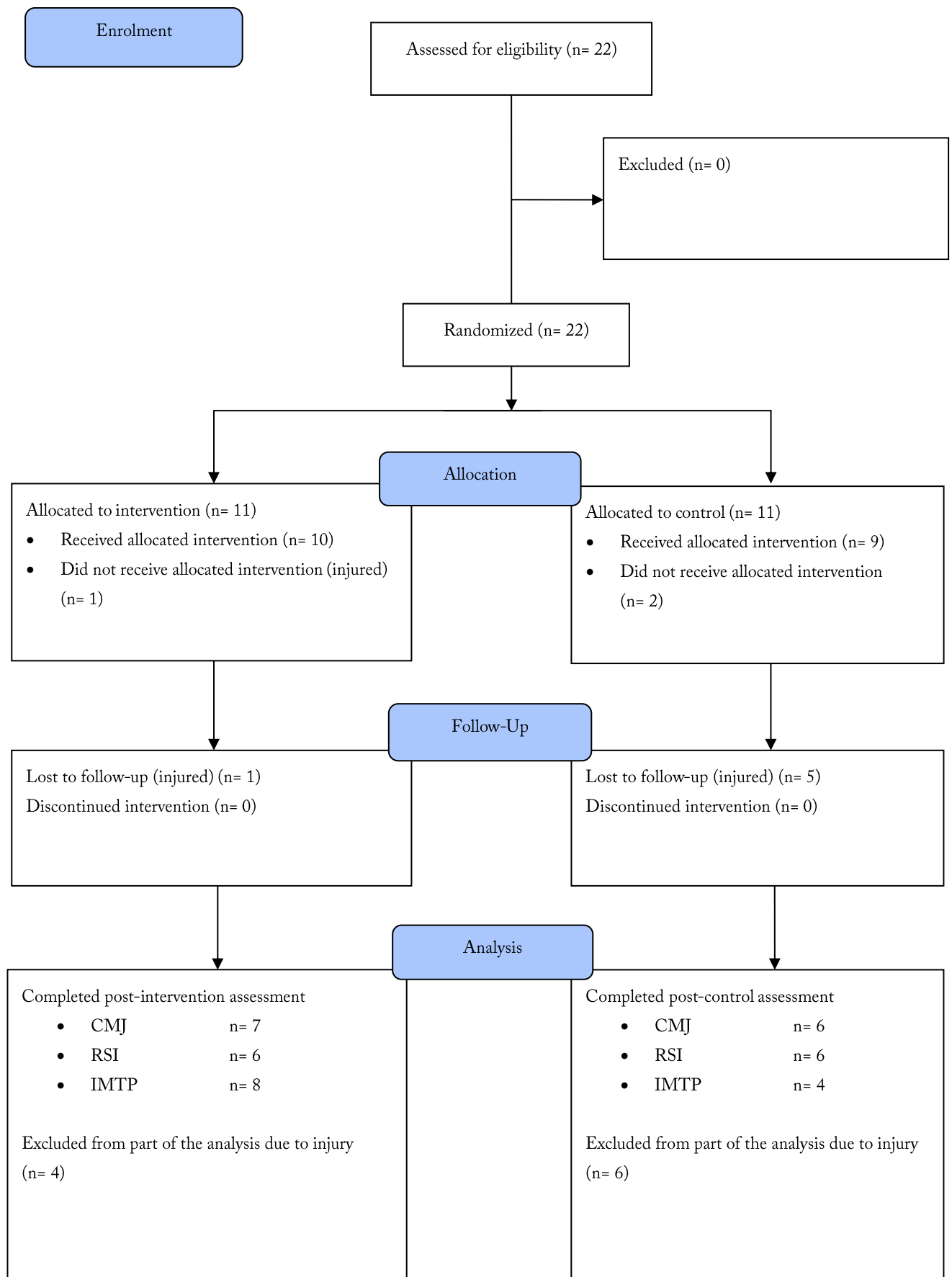


Table 6-1. Participants characteristics for age, weight, height and BMI

	Overall (n= 22)			Intervention (n= 11)		Control (n= 11)	
	Total	Male	Female	Male	Female	Male	Female
n	22	5	17	3	8	2	9
Age (years)	16.6±.52	17.1±.87	16.5±.27	16.8±.45	16.8±.33	17.5±1.44	16.5±.23
Weight (kg)	54.9±8.94	65.3±5.3	51.8±7.32	63.4±5.58	50.3±8.04	68.3±4.6	53.1±6.82
Height (cm)	170±8.0	179±6.0	168±6.82	175±2.75	166±7.37	184±6.29	169±6.4
BMI (kg·m ²)	18.7±1.6	20.4±0.91	18.3±1.36	20.6±1.24	18.1±1.38	20.1±.02	18.4±1.39

6.5 Discussion

The present feasibility trial was characterised by high attrition rates. This may be related to the existing high load in dance hours this group had (n= 27hrs/wk⁻¹). The extra total hours (n= 2.5hrs/wk⁻¹) of conditioning required by the intervention protocol may have been more than what the participants could tolerate. Future studies with an exercise program as an intervention should consider the current load of the participants and try and incorporate the intervention as part of the existing load and not as an additional component of the total workload.

The high level of intervention adherence in the first two weeks may have been due to the novelty-effect as the participants reported to be very motivated to take part in the workout. The novelty-effect has been associated with the use of activity tracker devices (Shin et al., 2018), even though this intervention did not involve technology, it speculated that this type of training was a novelty, as the participants referred to it going *against tradition*. To avoid the interference of the novelty-effect the intervention needs to be longitudinal, with a clear

progression in the exercises in order to keep the stimuli interesting and exciting for the participants. Considering the observed low adherence, further studies need to take this into account for the sample selection and/or sample calculation, either by setting a cut-off point (Murtagh et al., 2005) for adherence or apply the intention-to-treat principle (Gupta, 2011). There are pros and cons for both approaches. A cut-off point ensures that a participant that did not receive the treatment or participate in the intervention is included as a participant who did as this may affect the efficacy of the intervention (Gupta, 2011). In contrast, even though intention-to-treat analysis has been criticised for being too cautious and therefore, being more susceptible to type II error (Hollis and Campbell, 1999, Fergusson et al., 2002), the pros outweigh the cons. Intention-to-treat is a reflection of the practical clinical setting as it admits noncompliance and protocol deviations. Intention-to-treat also offers an unbiased estimate of treatment/intervention effect (Wertz, 1995, Heritier et al., 2003, Montori and Guyatt, 2001). In addition, participants may drop out from the study or not participate enough in the intervention as a response to the intervention (Wertz, 1995), therefore, important information about any potential adverse effects may not be reported if they are excluded from the analyses. Furthermore, with intention-to-treat sample size is preserved and type I error is minimised due to cautious approach. This in return improves the generalisability of the results (Montori and Guyatt, 2001).

The assessment was not perceived time consuming, however, participants dropped out from both the pre and post-tests, mainly because of injury. Potential drop-out due to injury, therefore, needs to be taken into consideration in further studies with exercise related interventions.

The adverse effects that were reported may be related to a potential training effect that caused delayed onset muscle soreness (DOMS). Muscle soreness post a training stimuli may result in significant muscle damage in both recreational and elite athletes, if they are unaccustomed to the stimuli (Pyne, 1994), especially if the exercise involves a large amount of eccentric contractions (Clarkson and Hubal, 2002). There was no gender difference in the reporting of muscle soreness (Clarkson and Hubal, 2002). The intervention involved exercises with some sub-plyometric activity in the take-off and landing technique part. Even though the participants were instructed to *land softly*, it seems that the external load applied exceeded the muscle's ability to actively resist the load, therefore, the muscle was forced to lengthen (Cheung et al., 2003), beyond the range of movement the participants were used to. DOMS is particularly prevalent in resistance training (Connolly et al., 2003), however, the intervention was based on bodyweight exercises. It is hypothesised that the participants were not only unaccustomed to this type of exercise but also to the feeling of muscle soreness too. This may be mainly because of the lack of supplementary training and the ballet-only approach of training (Koutedakis and Jamurtas, 2004).

Even though the muscle soreness was not reported as an inhibitor to carry out the tasks of the ballet class, what was a potential reason to the drop-out was the perception that DOMS was related to muscle hypertrophy (*I don't want my thighs to bulk up*), and potential loss of the aesthetic look, an unfounded view prevalent in sections of the dance world (Koutedakis and Jamurtas, 2004). Further studies need to consider the education of the participants on the potential effects of the intervention a priority.

Overall, the physiological reaction from the workout as reported from the participants suggests potential training effects, however, the initial dosage may not have been correct. Further research would need to take this into account so that the introduction and loading is more gradual and progressive.

6.5.1 Strengths and limitations

This is the first feasibility randomised trial in adolescent ballet dancers to assess the intervention adherence and fidelity prior to further investigations. Information on the reasons of drop-out was collected, however, one major limitation is the fact the adverse effects the participants reported were not quantified, even though it wasn't in the scope of this study this information would have been useful for further studies. Both groups were given clear instructions not to share information about the intervention, however, since this was a single-centre trial, it is possible that there may have been intervention contamination from the control group.

6.6 Conclusion

The results from this study reveal that a randomised controlled trial on the effects of neuromuscular training may be feasible in a vocational dance education setting, with certain necessary amendments to control for the increased rate of attrition that was reported. The inclusion of any exercise intervention in the existing load of the students instead of extra load may be more effective to control for the high attrition that was observed in the current study. The participants need to be informed about the potential adverse effects, and education is vital,

especially for the female dancer in order to debunk unfounded myths regarding supplementary training and muscle hypertrophy. Even though this feasibility study indicated potential training effects from the use of neuromuscular training, these effects were not recorded in the post-tests, due to the high drop-out rate. Further trials on the effects of neuromuscular training in adolescent dancers are required for a clearer picture to be drawn.

7 The effects of neuromuscular training on physiological parameters in adolescent ballet dancers: a randomised controlled pilot trial

7.1 Background

Having established the extend of the injury problem and the associated risk factors and mechanisms, it is reasonable to investigate injury prevention strategies (Finch, 2006), in order to protect and support the young dancer's development and potentially his/her carrier.

Generally injury prevention strategies focus on injury risks (Rössler et al., 2016a). Injury risk factors can be classified as modifiable or intrinsic and non-modifiable or extrinsic (Emery, 2003, DiFiori et al., 2014). Multifaceted injury prevention programs containing neuromuscular strength training and/or proprioception training aim at altering these modifiable intrinsic factors (e.g. power, strength, balance and proprioception) (Lauersen et al., 2014), with no additional equipment (Herman et al., 2012). A randomised controlled trial with young futsal players (n= 36), assessed the effectiveness of the FIFA 11+ injury prevention intervention that was developed by the Fédération Internationale de Football Association. The study revealed that after 12 weeks, the intervention group improved significantly in jumping ability (squat jump 13.8%, countermovement jump 9.9%), sprinting (5m 8.9%, 30m 3.3%), agility (4.8%) and balance (decreased falls during the assessment by 30%) (Reis et al., 2013).

In dance, the relationship of physiological parameters and injuries is unclear. A systematic review on the relationship of muscular strength and dance injuries revealed that the current state of the art is based on studies with certain methodological issues, such as no randomisation, small samples, short duration (Moita et al., 2017). In addition, given the rigorous training

demands in dance, and the potential life-changing impact injuries can have on young ballet dancers, it is both surprising and concerning that intervention research is lacking in dance (Caine et al., 2015). It is therefore plausible to evaluate neuromuscular training with regards to its effects on physiological parameters such as power, strength and potential strength imbalances.

It has been argued that it is not always feasible to randomise participants in youth sport (Emery, 2010), however, the feasibility of a randomised controlled trial was demonstrated in chapter 6. The results were not informative enough to conduct power and sample calculations. For this reason, a pilot study is deemed as a necessary preliminary step, as it is not a hypothesis testing study and therefore, efficacy and effectiveness are not assessed with it (Whitehead et al., 2014). It has been suggested that power and sample calculations should be conducted with caution when using data from a pilot study (Kraemer et al., 2006), however, in the absence of any robust meta-analysis on the clinical significance of any physiological markers within the selected population together with the existing poor data in the literature this randomised controlled pilot trial was conducted to collect data for a power and sample size calculation, for a further trial.

7.2 Aims and hypothesis

The aim of this pilot study, therefore, was to investigate the effects of a neuromuscular training workout on countermovement jump (CMJ), reactive strength index (RSI), isometric mid-thigh pull (IMTP) and inter-limb asymmetry (ASYM) compared with usual training. The null

hypothesis was that there would be no significant between-group differences in the outcomes. The main objective was to conduct power and sample calculations using the mean CMJ scores for a further randomised controlled trial.

7.3 Methods

Guided by the results of the feasibility study presented in chapter 6, the research protocol was amended for the present study. The teachers and the students from the two first year groups of school were approached and presented with the idea of a randomised controlled pilot trial. It was proposed to the teachers to dedicate 30 minutes of what they would normally do as a warm-up/conditioning workout for the students at the beginning of their daily ballet class for seven weeks. The purpose and process of the randomisation together with the potential adverse effects (i.e. delayed onset muscle soreness) of the intervention was explained to both the teachers and the students. All the participants were advised not to discuss between the groups either the intervention or the usual training. Study details are presented according to the CONSORT guidelines (Moher et al., 2010).

7.3.1 Trial design

The randomisation process is described in detail in chapter 6, section 6.3.1. The study was conducted in a vocational ballet school with elite adolescent dancers in Birmingham, United Kingdom during the last term of the year (May- June 2017).

7.3.2 Outcomes

Analysis was conducted based on the intention-to-treat principle (Gupta, 2011). The primary outcomes were the height of the CMJ, and the secondary outcomes were the RSI, IMTP, inter-limb asymmetry (ASYM). Exposure (adherence) was measured through the attendance records that were updated daily for both groups and interviews with the individuals who missed sessions were conducted by the Principal Investigator (PI) to identify the reasons for their absence. Exposure for both groups was defined as the percentage of total sessions of participation. Participants who reported an injury were assessed by the physiotherapist.

7.3.3 Participants

The students at the school are split according to chronological age. Research in an applied setting as such entails a few limitations. Whole year-groups, therefore, needed to be included in the study for the creation of the sample. The sample size was increased, however, sample size calculation for the pilot study was not conducted.

Forty-two elite adolescent ballet dancers and four ballet teachers volunteered to participate in this study. All participants had to be cleared by the medical centre of the school in order to take part in the study. Any participant who was unable to take part in the pre-testing and was diagnosed with an injury by the physiotherapist of the school was excluded from the analysis. The participants were all exposed to same amount of dance hours per week ($n = 19 \text{ hrs wk}^{-1}$). The ballet teachers had substantial experience (≥ 10 years) in teaching adolescent dancers.

7.3.4 Procedures

A detailed description of the procedures is presented in chapter 6, section 6.3.5

7.3.5 Jumps

The testing protocol for all the jumps utilised in this study is presented in more detail in chapter 6, section 6.3.7.

The participants performed three countermovement jumps (CMJ) bilaterally, three CMJs unilaterally and three drop jumps (DJ) from a 30 cm box in a non-fatigued state (Flanagan et al., 2008). Inter-limb asymmetry (ASYM) was assessed through the following equation (Bishop et al., 2018):

$$ASYM = 100 \div MAX(Left: Right) \times MIN(Left: Right) \times -1 + 100$$

The highest unilateral CMJs were used for analysis (Castagna and Castellini, 2013). Each participant had a 30 second recovery between CMJs (DiStefano et al., 2010). To avoid any potential cushioning effect from the footwear (Pickering Rodriguez et al., 2017), and to replicate the most common conditions the young dancers dance in, all jumps were performed barefoot.

For the unilateral CMJ, the participants were instructed to stand upright, with their feet hip width apart, and keep their hands akimbo throughout the jump. To begin the test, the participants had to lift one leg off the floor to approximately mid-shin height of the standing leg. The participants performed a squat to a self-selected depth followed by a fast upward vertical movement, triple extending at the hip, knee and ankle with an explosive intent to jump as high as possible (Bishop et al., 2018). The participants were also instructed to remain with the knee and ankle extended and land in the same position and location in order to avoid horizontal displacement which could have an effect on flight time (Chaouachi et al., 2017).

Lastly, they were instructed to land on the same leg. If the participants deviated from the instructions, they had to re-take the jump after a 60-second rest period (Bishop et al., 2018). Instructions for the CMJ included, *keep the flow of your movement, jump as fast and as high as you can, by pushing the earth away.*

7.3.6 Isometric Strength

The isometric mid-thigh pull testing protocol is described in detail in chapter 6, section 6.3.8

7.3.7 Intervention group

Level 1 and 2 exercises from the 11+Dance injury prevention intervention were used for the purpose of this study. The development of the intervention is presented in more detail in chapter 7. The pool of the selected exercises used in the workout were split into two sessions (1 and 2) which they were alternated daily to minimise the risk of motivation loss through training monotony (Rössler et al., 2016a, Anderson et al., 2003) (Table 7-1).

The participants from the intervention group were asked to take part in the workout before the ballet class five days per week. The intervention group was asked not to discuss the workout with the usual training group.

Table 7-1. Exercises included in the intervention workout

		Sets	Duration	Reps	Exercise	
Skipping	Week 1-3	3	1min		Two legs single-under	
	Week 4-5	3	1min		Alternate Single leg single-under	
	Week 6	4	1min		Alternate Single leg single-under	
	Week 7	5	1min		Alternate Single leg single-under	
	Week 8-9	1	3min		Travelling skips	
		Session 1		Level 1		
Phase 1	1	1	10-15sec	2 e/s	Plank on elbows - raise the leg	Increase time of hold
	2	1	10-15sec	2 e/s	Plank on hands - raise the leg	Increase time of hold
	3	1	10-15sec	2 e/s	Side Plank - on knee	On elbow and side of foot
	4	1		10 e/s	SL Bridge & Hold	Increase time of hold (3-5sec)
	5	1		8-10	Hamstring Raises	Increase reps to 12-15
	6	1-2		10	Squats to relevé	Slow Eccentric Phase
	7	1-2		8 e/s	Walking Lunges	Demi-Pointe to lunge
	8	1		8 e/s	Side Lunges	Increase reps to 12
Phase 2	9	1		10 e/s	SL Balance - Hip rotation	Increase speed
	10	1		10 e/s	SL Balance - Upper body rotation	
	11	1		10 e/s	Cross-Country Skiing	Increase sets to 2
	12	1		5-10 e/s	Hip Airplane	Increase height of the leg
Phase 3	13	1-2		10	Forward landings	Put the brakes on
	14	1-2		10	Side landings	
	15	1		8 e/s	SL Forward landings	
	16	1		8 e/s	SL Side landings	
		Session 2				
Phase 1	1	2		10 e/s	Plank on hands with elbow taps	Shoulder taps
	2	2		10 steps	Bear crawl -Static 3-point of contact	Forward/Backward
	3	2		10 steps	Crab walk - Static 3-point of contact	Forward/Backward
	4	1		8-10 e/s	Cook Hip lift	Increase sets to 2
	5	1		10	4-way Monster Walks-straight legs	Increase resistance
	6	1		10	4-way Monster Walks-bend legs	
	7	1-2		10	Squats with Overhead Reach	Hold dowel
	8	1		8 e/s	Side Slides	Increase reps to 12
Phase 2	9	1		10 e/s	Leg Swings forward	Increase speed
	10	1		10 e/s	Leg Swings Cross-body	
	11	1		12 e/s	SL Reach	Increase sets to 2
Phase 3	12	1-2		10	Forward landings	Put the brakes on
	13	1-2		10	Side landings	
	14	1		8 e/s	SL Forward landings	
	15	1		8 e/s	SL Side landings	

7.3.8 Usual training group

The participants in the control group participated in a 30 minutes workout before their daily ballet class. The workout was led by their ballet-teachers. The ballet-teachers were advised to perform their usual training and they received no instructions as to what exercises to include in their workout. The set of exercises the ballet-teachers used are presented in tables (Table 7-2, Table 7-3, Table 7-4, Table 7-5).

Table 7-2. Exercises included in the Usual Training workout for 12-year-old male dancers (A)

-
- In the centre standing in parallel: head exercises (look down, look up, look right (R) & left (L), tilt R/L, circle both directions), shoulders (circle R/L & both), arms (circle R/L & both, downward & upward movement R/L, both: clockwise, anti-clockwise), twisting torso R/L, pushing elbows backwards & flinging arms from elbows (to open chest area), also while moving forward & backward direction in a parallel plié, marching steps (on spot, moving forward & backward, turning R/L, small hops (on the spot & turning R/L), small hops on R/L leg (on the spot & turning R/L jumping jacks, spotty dogs, standing feet apart & parallel (turn body R/L to stretch over R/L legs, forward bend with hands on the floor, bend & stretch knees, roll up the spine).
 - Stand in ballet 1st position: ballet arms (look down, look up, look R/L, tilt R/L, circle head R/L)
 - Stand at the barre: limbering exercises (drop to deep plié, extend legs with flexed heels, return to upright position & on toes bend back). Taken 8 times. Exercises for feet (parallel & turned out using 1st, 2nd & 5th positions), rolling up & rolling down for knees and feet (using 1st, 2nd & 5th positions), pony trots (demi-toes & fully stretched feet) using two counts, 1 count & double time. Build to jogging on the spot, feet off the floor, knees up (all at the barre), then without barre building up momentum & continue in two circles around the studio, return to barre and backward motion of the lower legs: accelerating until music stops (for cardio).
 - Stretching at the barre: calves, knees, hamstrings (from a kneeling position & with legs on the barre), from turned out 1st position deep plié & stretch hamstrings & rotators extending legs to the side R/L, extensive stretching with legs on the barre (in front & out to the side, with stretched feet, bending of the body R/L & backwards), sliding along the barre for extra stretch, sliding along barre into hip joints to counter stretch opposite direction, kneeling in parallel position with the use of barre (extend legs behind body, then hands on floor to push toes towards head for hard-core stretch of spine), sit up with legs extended forward & jack-knife over legs. If there is time some sit ups for abdomen (optional) as this taken up at coaching class.
 - Skipping (optional) as this taken up at coaching class.
-

Table 7-3. Exercises included in the Usual Training workout for 13-year-old male dancers (B)

<ul style="list-style-type: none"> • Shoulders • Head • Arm Swings/ Alternative arms • Side stretches • Plank/ Plank with leg raises • Bridge/ Bridge with leg raises • Running on spot 8, Star Jumps • Press up/ and then in my conditioning class I add lats exercise on stomach and lats at the barre, Inner thigh exercise [floor] and sit up.
--

Table 7-4. Exercises included in the Usual Training workout for 12-year-old female dancers (A)

<ul style="list-style-type: none"> • 'Clams' lying on side with knees bent - shoulders in line with pelvis & feet below derriere - lifting top leg, with no movement of pelvis at all - performed to a slow 3/4 timing, taking 4 counts to lift & 4 to lower. 8 times with each leg. • Lying on side - top leg bent- knee on floor- underneath leg straight - lifts with underneath leg. 6 times with each leg. • On hands & knees with lower abs engaged & spine held straight...lengthen one leg behind [<i>en dedan</i>] at the same time extend opposite arm forwards - extending leg & arm for '5' counts; and bringing both to touch the floor together in count '8'. Twice consecutively x 6 • Lying on front with elbows bent & hands placed at temples - keeping head straight [not lifting] lift upper back off the floor, taking '8' counts to lift, hold & lower back to ground. 4 times. • Sitting on swiss ball - bounces 4 x '16' counts of music 2/4 time. • Balancing on knees on top of swiss ball - 4 x '16' counts of music 2/4 time. • Standing on one leg with eyes closed - core engaged, gluts engaged, awareness of correct stance through supporting foot - arms crossed across chest. 4 x '16' counts [steady 3/4 timing. Twice on each leg. • Demi plie x 2 followed by 3 x rises to demi pointe – core glutes engaged. Performed twice on each leg [slow 3/4 time] • Skipping with skipping rope for 1 minute.
--

Table 7-5. Exercises included in the Usual Training workout for 13-year-old female students (B)

<ul style="list-style-type: none"> • As year 7 Girls • '8' times with each leg • '6 - 8' repetitions • '6' times • As year 7 Girls • As year 7 Girls • '6' times including 2 x demi plies [<i>en sedan</i>] • Performed '3' times on each leg • Lying on back with knees bent parallel – elastic band over barre & with arms straight & ends of band in each hand - pull down to sides in '6' counts and release • Skipping with skipping rope for 1 1/2 / 2 minute

were asked not to be present in the studio while the intervention group was doing the intervention workout in order to avoid trial contamination by exposing the control group to the intervention. The control group was not given any instructions as to what to do before the ballet class.

7.3.9 Statistical analysis

The mean scores of the post-CMJ for both groups together with their standard deviations were used to conduct the power and sample calculations.

The primary outcome of this exploratory analysis was the CMJ, and the secondary outcomes were RSI, IMTP, and ASYM (Caldwell et al., 2019). Repeated measures analysis of variance (RM-ANOVA) was conducted to investigate whether there was a statistically significant difference between the Intervention and the Usual training programs on CMJ, RSI, IMTP and ASYM. Effect sizes were calculated using partial eta square (η_p^2), with values of .0099, .0588, and .1379 defined as small, medium, and large effects, respectively (Richardson, 2011).

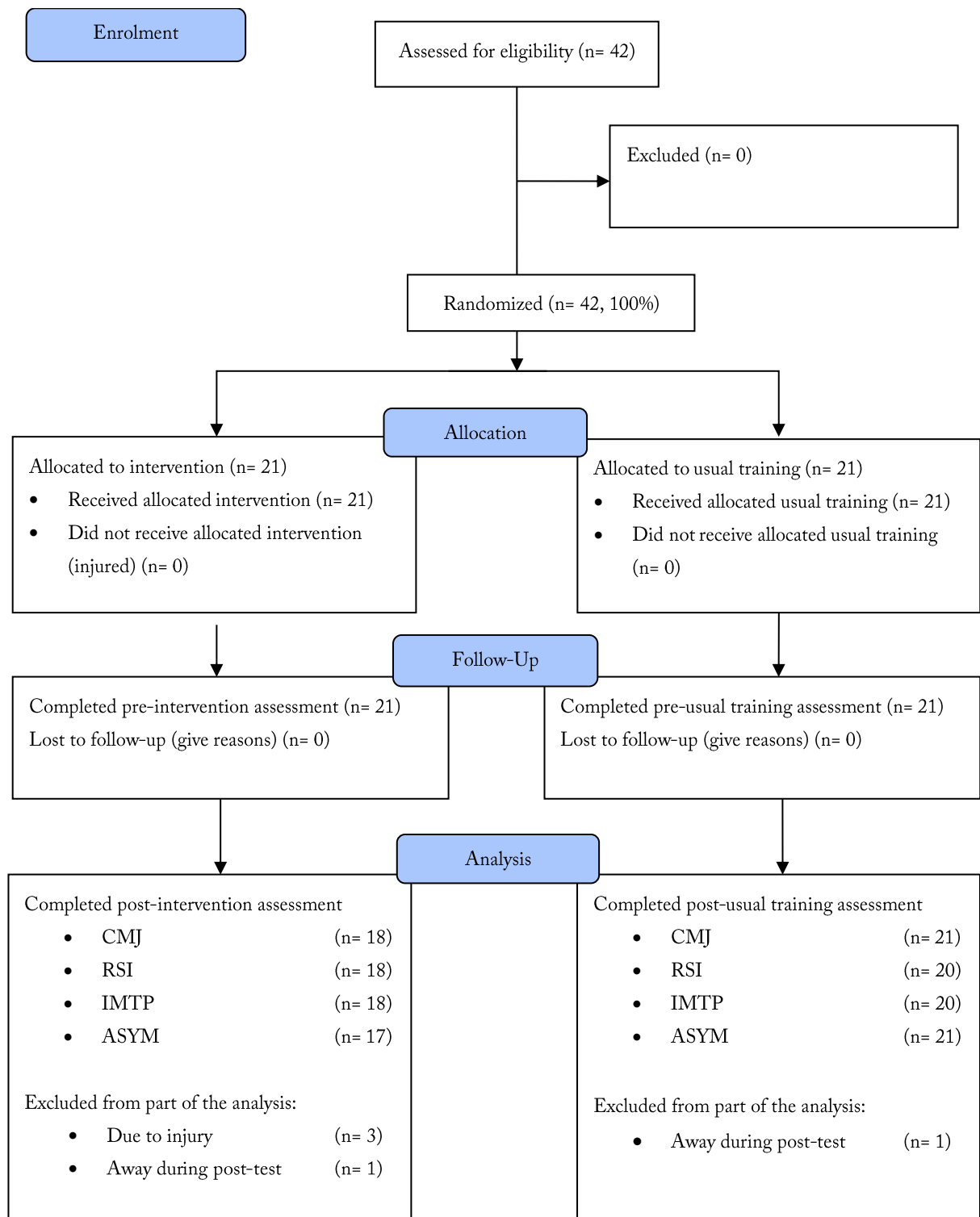
Independent Student's t-tests for the differences (delta) for all the parameters were conducted to get a between-group mean difference with 90% confidence intervals (90% CI). Analyses was conducted using the statistical software Jamovi (version 1.0) retrieved from <https://www.jamovi.org>, whereas the power analysis was conducted using the software G*Power (version 3.1.9.2).

7.4 Results

7.4.1 Flow of participants through the trial and recruitment

Forty-two adolescent elite dancers were randomised into the Intervention or Usual training group. During the follow-up, four participants (19%) from the intervention group and one participant (5%) from the usual training group were lost for part of the testing battery due to injuries reported by the in-house physiotherapist (for details Figure 7-1). Post testing took place on the weekend after the last day of the intervention.

Figure 7-1. Trial flowchart



7.4.2 Participant characteristics at baseline

Baseline characteristics of the 42 participants (mean \pm SD, age= 12.7 \pm .58 years; weight= 40.0 \pm 6.5 kg; height= 155.0 \pm 7.1 cm; BMI= 16.5 \pm 1.5 kg \cdot m²) are provided in Table 7-6.

Table 7-6. Descriptive characteristics of the participants at baseline

	Overall (n= 42)			Intervention (n= 21)		Usual Training (n= 21)	
	Total	Male	Female	Male	Female	Male	Female
n	42	18	24	8	13	10	11
Age (years)	12.70 \pm .58	12.65 \pm .55	12.75 \pm .61	12.85 \pm .63	12.85 \pm .58	12.5 \pm .47	12.62 \pm .65
Weight (kg)	40.0 \pm 6.5	43.1 \pm 6.4	37.6 \pm 5.6	43.3 \pm 7.5	38.8 \pm 4.2	43.0 \pm 5.8	36.2 \pm 6.1
Height (cm)	155.0 \pm 7.1	156.7 \pm 7.5	153.7 \pm 6.6	157.3 \pm 7.5	155.3 \pm 6.4	156.2 \pm 7.9	151.9 \pm 6.6
BMI (kg \cdot m ²)	16.5 \pm 1.5	17.4 \pm 1.1	15.8 \pm 1.4	17.4 \pm 1.4	16.1 \pm 1.1	17.5 \pm .9	15.5 \pm 1.7

7.4.3 Outcomes

With a power of 80%, an alpha of 5%, and using the group post-means and standard deviations of the primary outcome (CMJ), an *a-priori* sample calculation revealed that 55 participants in each group (n= 110) would be required for the following trial.

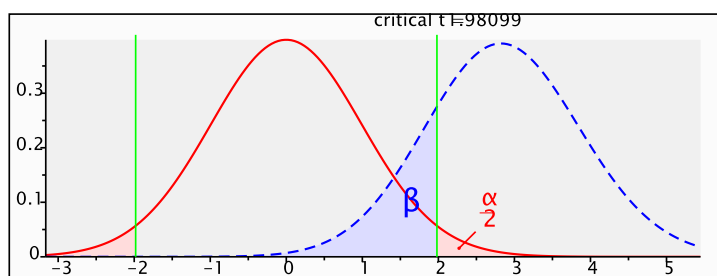


Figure 7-2. Power analysis for two-tailed independent groups t-tests based on the CMJ post-test scores for both groups (mean \pm SD), CMJ_{intervention}= 26.8 \pm 4.04cm, CMJ_{usual training}= 24.7 \pm 3.74

The plot in Figure 7-2 is the G*Power output, whereby the green line shows the critical t value and the blue area on the left of the line represents the Type II error rate. When the t value is on the right of this blue area, the null hypothesis can be rejected.

The ANOVA [between-groups (by time) factor: group (intervention, usual training)] revealed no significant effect of the intervention on CMJ, $F(1, 37) = 1.21$, $p = .279$, $\eta_p^2 = .032$. No significant effect of the intervention was also revealed for RSI, $F(1, 36) = 0.554$, $p = .462$, $\eta_p^2 = .015$. Similarly, there was no significant effect either for IMTP, $F(1, 37) = 0.265$, $p = .61$, $\eta_p^2 = .007$ or ASYM, $F(1, 35) = 0.357$, $p = .554$, $\eta_p^2 = .01$.

Pre-post mean differences together with standard deviations and standard errors for all the parameters can be seen in Table 7-7, whereas the means for the differences (delta) together with the 95% confidence intervals for CMJ (Figure 7-3), RSI (Figure 7-4), IMTP (Figure 7-5), and ASYM (Figure 7-6) are presented below.

Table 7-7. Pre-post mean differences, standard deviation, and standard error for CMJ, RSI, IMTP and ASYM

	Group	N	Mean	Median	SD	SE
Delta CMJ	Intervention	18	3.5167	3.1500	2.850	0.6717
	Usual training	21	1.933	1.8000	2.368	0.5168
Delta RSI	Intervention	18	0.0356	0.0400	0.180	0.0424
	Usual training	20	0.106	0.0600	0.172	0.0385
Delta IMTP	Intervention	18	133.1500	150.0000	183.392	43.2259
	Usual training	21	112.824	110.2000	170.310	37.1647
Delta ASYM	Intervention	17	-1.9506	-3.8200	7.247	1.7577
	Usual training	20	-1.273	-1.0550	8.612	1.9258

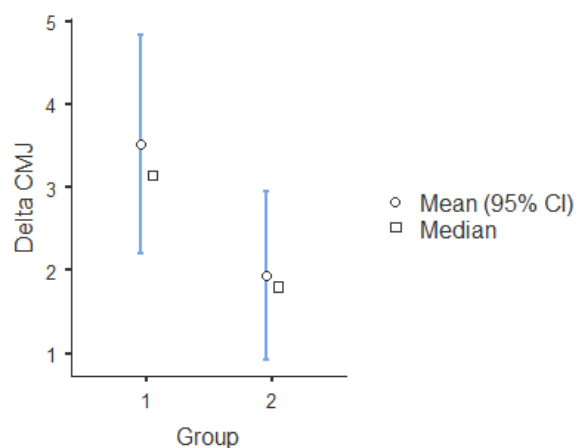


Figure 7-3. Mean for the difference (delta) (95% CI) for CMJ between the intervention (1) and usual training (2) groups

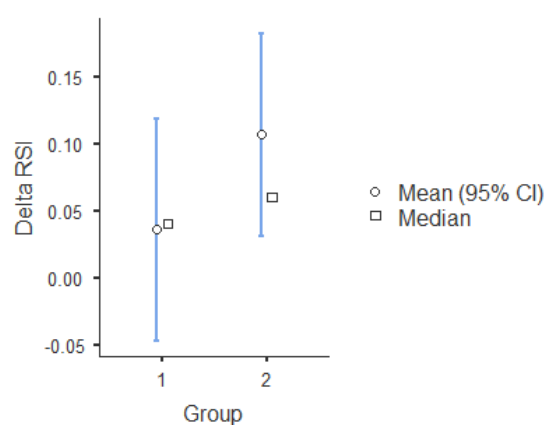


Figure 7-4. Mean for the difference (delta) (95% CI) for RSI between the intervention (1) and usual training (2) groups

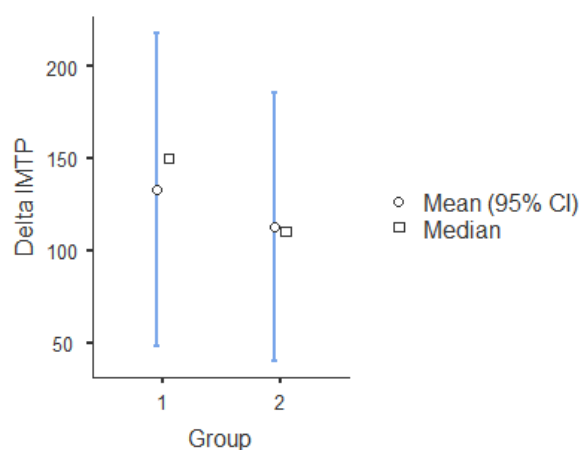


Figure 7-5. Mean for the difference (delta) (95% CI) for IMTP between the intervention (1) and usual training (2) groups

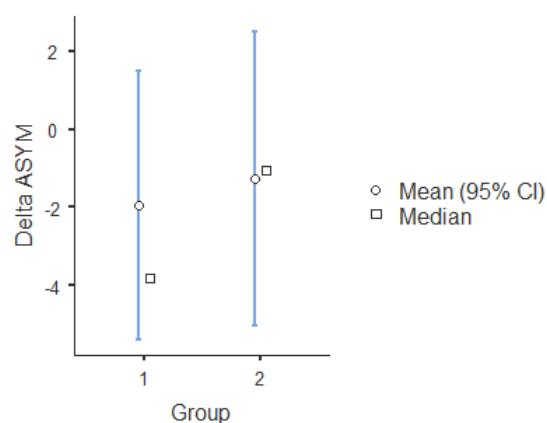


Figure 7-6. Mean for the difference (delta) (95% CI) for ASYM between the intervention (1) and usual training (2) groups

7.4.4 Feasibility of the intervention

The total number of sessions for the duration of the trial ($n=7$ weeks) was 35. Adherence for both groups was high, the intervention group completed (mean \pm SD) $71\pm17\%$ of all sessions, whereas, the usual training group completed $75\pm10\%$ of all sessions. The minimum number of

sessions participants completed in the intervention group was 6 (17%) and the maximum was 33 sessions (80%). For the usual training group, the minimum number of sessions was 14 (40%) whereas the maximum was 28 (80%). Illness and injury/pain were the main reasons for not participating in a session.

7.4.5 Feasibility of the outcome measures

Pre and post testing lasted approximately five minutes per participant. Participants were invited in groups of three to avoid long waiting time. Post-testing took place on the Saturday after the last Friday of the intervention completion.

7.4.6 Adverse effects

Similar to the feasibility study, muscle soreness was the main adverse effect the participants reported. After the first two weeks, there was one-week half-term break, and the muscle soreness feeling faded away, but was reported again when the intervention commenced after the break. These adverse effects were not reported to be an inhibiting factor for the participants to complete the tasks of their class.

7.5 Discussion

This pilot study revealed that the sample size for a further confirmatory randomised trial needs to be 55 participants in each group. Even though this study was not conducted to assess the efficacy of the intervention in comparison to usual training, it is still interesting to note that both groups improved over the time of the study. No significant differences were detected in the scores in either the primary or the secondary outcomes.

The improvements that were observed for both groups, indicate that supplementary training may be inducing physiological adaptations for adolescent dancers irrespective of the type of training (neuromuscular or usual training). In the absence of any randomised trials with a similar population in the literature there are no reference data available to compare the reported findings with.

The adherence was higher than that reported from the feasibility trial (see 6.4.1). The main reason for this may be that the workout was incorporated as part of the participants' existing load unlike the procedure of the feasibility study. Also, the participants agreed to volunteer to do this workout at the beginning of their class, therefore, they may have perceived it as obligatory. If a participant, however, did not want to participate but felt uncomfortable to discuss or inform the principal investigator, they were advised that they can inform their personal tutor, houseparent, or any of the medical staff. This channel of communication was set for the participants to avoid forced participation through the power relationship between the coach (principal investigator) and the participants (Cushion and Jones, 2006).

Even though the participants reported the same adverse effects as in the feasibility study, these effects do not seem to have affected adherence. One reason may be that the participants had a lower total of dance hours during the week than the participants of the feasibility study. Moreover, the intervention run during the last term of the year which means that the participants may have been more conditioned from the accumulated load of the year.

Similar to the feasibility study results the adverse effects may be related to a potential training effect that caused delayed onset muscle soreness (DOMS), mainly because the participants were unaccustomed to this type of training (Pyne, 1994). The sub-plyometric activity in the

skipping, and the take-off/landing technique training involve high eccentric muscle contractions, which may partly explain the muscle soreness (Clarkson and Hubal, 2002). Moreover, even though all the exercises were performed with no external load (Connolly et al., 2003), they seem to have produced a potential training effect from the forceful lengthening of the muscles during these activities (Cheung et al., 2003), as it is beyond the range of movement the participants were used to. Similar movements to the bilateral (e.g. squats, landing bilaterally) or unilateral (e.g. lunges, cross-country skiing, single-leg landing), are performed in the ballet class (e.g. *plie*, *jetes*), however, the range of movement is different as movement in ballet restricts the flexion and extension of the hips while jumping. It was hypothesised that even though the participants were unaccustomed to the type of exercises included in the intervention program, the clear description of the potential adverse effects of the intervention, made DOMS less of a surprise to the participants and potentially easier to cope with. On the contrary, no adverse effects were reported from the usual training group, this may be because the exercises the ballet-teachers used were not new to the participants.

Finally, it is worth noting that contrary to the feasibility study, increased motivation from the dancers to participate was observed. Even though the assessment of the participants' satisfaction is beyond the scope of this study, it is speculated that the use of the gym, a place that has been associated with an element of *fun*, together with the novelty effect may have improved the participants' satisfaction. This in return may have improved the intervention adherence and fidelity and potentially made the adverse effect of muscle soreness easier to handle, however, this is a hypothesis that needs to be investigated further.

7.5.1 Strengths and Limitations

This is one of the first randomised controlled pilot trials, with blinding for the assessment of the outcomes. The single-centre approach together with the fact the participants shared other classes together may have contributed to potential intervention contamination. It is speculated, however, that the exposure of the usual training group to an exercise program may have controlled the risk of contamination. When researchers perform their own pilot study, potential bias from the researchers' degrees of freedom may arise (Albers and Lakens, 2018), however, the results were not used to assess the efficacy of the intervention, and the power analysis process has been clearly presented.

7.6 Conclusion

The results from this study reveal that incorporating an exercise-based intervention in the existing load of the dancers may influence positively the participants' adherence. Clarity and transparency of the trial process and the potential adverse effects from the intervention may have prepared the participants and, therefore, may have been more receptive and less likely to drop-out. Consistent with the feasibility trial, the delayed onset muscle soreness that was reported by the participants indicates potential training adaptations, but no significant differences were observed on any of the outcomes that were investigated. A larger trial on the effects of neuromuscular training in adolescent dancers is required.

8 The effects of 11+Dance on physiological parameters in adolescent ballet dancers: a randomised controlled equivalence trial

8.1 Background

It has been clearly demonstrated in this thesis that in the past decade large sports organisations have invested in the development of injury prevention programmes (for more details see chapter 2, section 2.8). In addition, the effectiveness of lower extremity injury prevention programmes in team-sport athletes has been supported by numerous systematic reviews (24 studies, $n \approx 250,000$) (Brunner et al., 2019). Surprisingly, there is currently no established injury prevention program for pre-professional and professional dancers (Caine et al., 2015).

Based on the epidemiological data that was presented in chapter 4 and guided by the large volume of high-quality literature on injury prevention in youth sport, the 11+Dance was developed; an injury prevention program specifically tailored for dancers. The theoretical framework of the 11+Dance is described in detail in chapter 5.

Several injury prevention studies in youth football have indicated that the use of neuromuscular interventions induce meaningful motor performance in strength, sprint and power (Reis et al., 2013, Rössler et al., 2016a, Zarei et al., 2018). It is, therefore, reasonable to evaluate the effect of this newly developed programme (11+Dance) on motor performance.

The program focuses on local muscular endurance in the trunk musculature and the lower body, balance and proprioception, ankle, knee, and hip alignment together with take-off and landing technique.

8.2 Aims and hypothesis

The aim of this study is to assess the effect of the 11+Dance program on the following physiological parameters, countermovement jump (CMJ), reactive strength index (RSI), isometric mid-thigh pull (IMTP) and inter-limb asymmetry (ASYM) compared with the Usual Training workouts. The null hypothesis is that there will be no between-group difference in either the primary (CMJ) outcome or secondary (RSI, IMTP, ASYM) outcomes.

8.3 Methods

Detailed description of the methods for this trial can be seen in chapter 6, sections 6.3 and chapter 7, section 7.3.

Since all the trials were conducted in the same centre, the participants from the pilot took part in the current trial too subsequently some of the participants were exposed to the intervention twice due to the randomisation process. Even though there was a wash-out period of eight weeks, an exploratory *post hoc* subgroup analysis (Higgins and Green, 2011) was deemed necessary for all the participants who were exposed to the intervention for the first time (New Starters) to ensure the reported results were not affected from a potential learning effect. The data from both the intervention and the usual training group, therefore, were used to conduct this analysis for the New Starters. For details please see the trials flowchart in Appendix 1, and the New Starters trial flowchart in Appendix 2.

Study details are presented according to the CONSORT guidelines (Moher et al., 2010).

8.3.1 Trial design

The trial design has been presented earlier in chapter 6, section 6.3.1 and was conducted during the first term of the year (September- November 2017) in a vocational school.

8.3.2 Outcomes

The primary outcomes were the height of the CMJ, and the secondary outcomes were the RSI, IMTP, inter-limb asymmetry (ASYM). Exposure (adherence) was measured through the attendance records that were updated daily for both groups and interviews with the individuals who missed sessions were conducted by the PI to identify the reasons for their absence. Exposure for both groups was defined as the percentage of total sessions participation. Participants who reported an injury were assessed by the physiotherapist.

8.3.3 Participants

The *a-priori* power and sample calculation from the pilot trial revealed that with a power of 80%, an alpha of 5%, and using between-group means change, 55 participants in each group (n= 110) were required. Five year-groups of the school would need to participate to achieve this number of participants, however, this was not feasible due to the scheduling implications the trial would have in the weekly program.

Seventy-five elite adolescent ballet dancers and four ballet teachers volunteered to participate in this study. All participants had to be cleared by the medical centre of the school in order to take part in the study. Any participant who was unable to take part in the pre-testing and was diagnosed with an injury by the physiotherapist of the school was excluded from the analysis.

The participants were all exposed to same amount of dance hours per week ($n = 19 \text{ hrs wk}^{-1}$).

The ballet teachers had substantial experience (≥ 10 years) in teaching adolescent dancers.

8.3.4 Procedures

The participants were randomly assigned to either the 11+Dance or the Usual training group via a number-generator program (Microsoft Excel) and by an independent blinded researcher. Anthropometric data was collected at baseline. Baseline data were collected by the principal investigator whereas post-test data were collected by a blinded independent assessor. Testing for both groups commenced with a dynamic warm-up. Ethical approval was attained from the University of Wolverhampton ethics committee.

Jump height and the reactive strength index (RSI) were measured with an Optojump Next system (Microgate, Version 1.10.19). The participants performed three countermovement jumps (CMJ) bilaterally, three CMJs unilaterally and three drop jumps (DJ) from a 30 cm box in a non-fatigued state (Flanagan et al., 2008). The highest scores for all the CMJs were used for the analysis (Castagna and Castellini, 2013), whereas the average contact and flight time was used to calculate the reactive strength index (RSI) (Ayala et al., 2017b).

8.3.5 Isometric Strength

The isometric mid-thigh pull (IMTP) testing protocol is presented in detail in chapter 6, section 6.3.8.

8.3.6 Intervention group

The participants were asked to arrive at the gym at the start of their daily ballet class five times per week. The “11+Dance” program consists of neuromuscular-based exercises. The focus of

the program is on muscle activation, local muscular endurance, ankle, knee, hip alignment, balance, and coordination, together with take-off and landing technique. The workout is split in three parts, Part 1: activation and local muscular endurance, Part 2: balance and coordination and Part 3: bilateral and unilateral take-off and landing technique. The pool of the selected exercises used in the workout were split into two sessions which they were alternated daily to minimise the risk of motivation loss through training monotony (Rössler et al., 2016a, Anderson et al., 2003). A full description of the development of this program is given in Chapter 5, section 5.5.

8.3.7 Usual training group

The participants randomised to the usual training arm performed exercises they would normally do with their teacher for 30 minutes before their ballet class. The four teachers who participated in the intervention selected their own exercises, with no instructions from the PI. Usual training included exercises for local muscular endurance, core musculature activation, balance, and proprioception. Examples of these workouts can be seen in chapter 7, Table 7-2, Table 7-3, Table 7-4, Table 7-5.

8.3.8 Statistical analysis

Analysis was conducted based in the intention-to-treat principle (Gupta, 2011). The primary outcome of this prespecified analyses (Cumming, 2014) was the CMJ, and the secondary outcomes were RSI, IMTP, and ASYM. One-way Analysis of Covariance (ANCOVA) was conducted to determine a statistically significant difference between the 11+Dance and the Usual training programs on CMJ, RSI, IMTP and ASYM, controlling for the baseline scores and adherence. Effect sizes were calculated using partial eta square (η_p^2), with values of .0099,

.0588, and .1379 defined as small, medium, and large effects, respectively (Richardson, 2011).

An exploratory analysis of the injury incidence between the two groups will also be reported.

In the case of null findings in the primary and/or the secondary outcomes, equivalence testing was utilised to assess whether the intervention is equivalent or not with the usual training.

When testing for equivalence, the test is conducted to assess whether the intervention effect is inside a prespecified equivalence margin $[\Delta L, \Delta U]$ with the two one-sided tests (TOST) procedure. The difference Δ can either be defined by standardized differences (e.g., Cohen's d) or raw differences (e.g., 0.3 scale point on a 5-point scale) (Lakens, 2017). The equivalence of the intervention is established when there is enough evidence that its efficacy is within Δ units from the usual training (Walker and Nowacki, 2011), which means that the between-group difference is smaller than the smallest effect size of interest (Lakens et al., 2018). The null hypothesis, therefore, is the presence of a true effect of ΔL or ΔU , and the alternative hypothesis is either the absence of an effect that is worthwhile to examine or the effect that is within the equivalence bounds (Lakens, 2017).

When used together with null hypothesis significance tests (NHST), four outcomes are possible for a study: 1) statistical equivalence, whereby the effect is larger than ΔL but smaller than ΔU and not statistical difference from zero, 2) statistical difference from zero but not statistical equivalence, 3) statistical difference from zero and statistical equivalence or 4) neither statistical difference from zero nor statistical equivalence i.e. inconclusive outcomes (Lakens, 2017). For this study the equivalent bounds are set as $\Delta L = -.3$ and $\Delta U = .3$, whereas effect size values (d) of 0.2, 0.5 and 0.8 were considered small, medium and large respectively (Cohen, 1988).

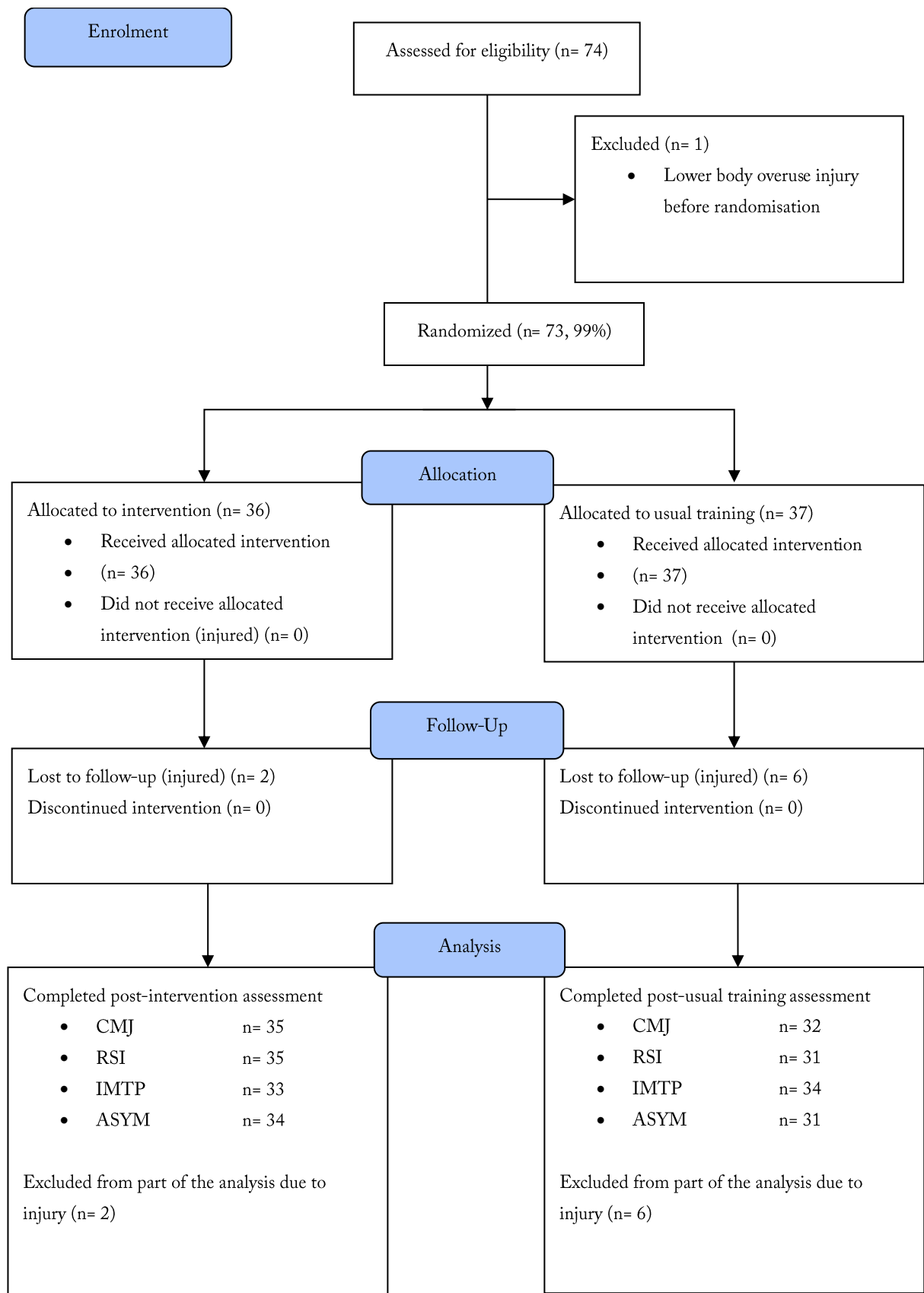
Analyses were conducted using the statistical software Jamovi (version 1.0) retrieved from <https://www.jamovi.org> and in R (R Core Team, 2014) whereas figures were produced using the package TOASTER (Lakens, 2017).

8.4 Results

8.4.1 Flow of participants through the trial and recruitment

One participant was diagnosed with a lower-limb overuse injury before the randomisation, therefore, seventy-three adolescent elite dancers were randomised into the 11+Dance or Usual training group. During the follow-up, two participants (6%) from the 11+Dance group and six participants (16%) from the usual training group were lost for part of the testing battery due to injuries reported by the in-house physiotherapist (for details see Figure 8-1).

Figure 8-1. Trial flowchart



8.4.2 Participants characteristics at baseline

Baseline characteristics of the 73 participants (mean±SD, age= 12.5±.87 years; weight= 39.1±8.44 kg; height= 154.0±9.3 cm; BMI= 16.4±1.9 kg·m²) are provided in Table 8-1.

Table 8-1. Participants characteristics at baseline for age, weight, height, BMI

	Overall (n= 73)			11+Dance (n= 36)		Usual Training (n= 37)	
	Total	Male	Female	Male	Female	Male	Female
n	73	30	40	14	22	19	18
Age (years)	12.5±.87	12.5±.94	12.5±.82	12.2±.87	12.7±.78	12.7±.94	12.3±.83
Weight (kg)	39.1±8.44	42.3±10.2	36.5±5.5	43.7±10.7	36.4±6.1	41.3±10	36.7±4.8
Height (cm)	154±9.3	154±11.6	153±6.95	156±11.3	153±6.8	153±12	153±7.4
BMI (kg·m ²)	16.4±1.9	17.5±1.9	15.5±1.4	17.7±2.2	15.4±1.6	17.4±1.6	15.5±.96

8.4.3 Feasibility of intervention

The 11+Dance group progressed to the level 2 exercises during the trial.

8.4.4 Outcomes

A *post hoc* power analysis revealed that with the current sample size, a small effect size ($d = .03$) and an alpha of 0.05 the achieved power was 24% (Figure 8-2. Post hoc power analysis). Mean differences for both groups for all the assessed parameters are presented in Table 8-2.

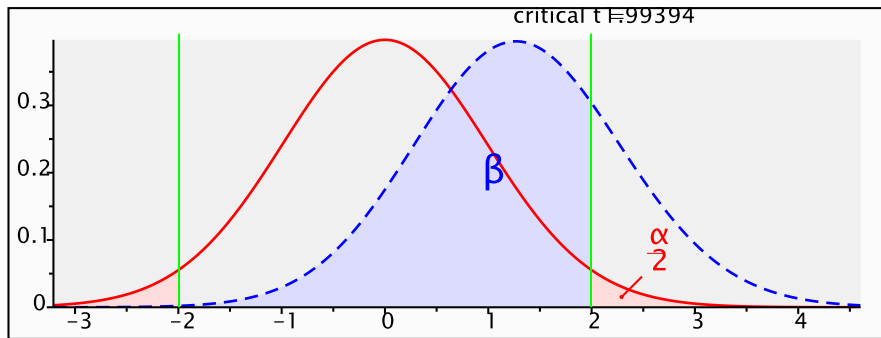


Figure 8-2. Post hoc power analysis

Table 8-2. Baseline and post intervention mean differences for CMJ, RSI, IMTP, ASYM for the 11+Dance and Usual Training groups

	11+Dance					Usual Training					Between groups mean difference (95% CI)
	n	Baseline (SD)	Post (SD)	Mean n (SD)	† Diff %	n	Baseline (SD)	Post (SD)	Mean (SD)	† Diff %	
CMJ (cm)	35	24.9 (3.6)	27.2 (4.2)	2.45 (2.8)	↑ 9	35	24.3 (4.4)	26.3 (4.8)	1.9 (2.3)	↑ 8	0.52 (-0.72, 1.76)
RSI	35	1.04 (0.26)	1.12 (0.24)	0.07 (0.1)	↑ 8	34	1.00 (0.31)	1.10 (0.31)	0.11 (0.2)	↑ 10	-0.03 (-0.12, 0.06)
IMTP (N)	35	805 (289)	967 (303)	183 (170)	↑ 20	36	766 (233)	901 (257)	135 (154)	↑ 18	49 (-30, 128)
ASYM (%)	35	12.5 (10.4)	9.1 (7)	-3.18 (12)	↓ 27	34	9.3 (6.6)	10.4 (8.8)	1.1 (11)	↑ 12	-4.26 (-9.9, 1.4)

$$\dagger \text{ Difference \%} = \frac{[Post-Pre]}{Pre} \times 100$$

The ANCOVA [between-groups factor: group (11+Dance, Usual training); covariate: baseline scores and adherence] revealed no significant effect of the 11+Dance on CMJ, $F(1, 63) = 0.25$, $p = .616$, $\eta_p^2 = .004$, there was a significant interaction between the baseline and post-intervention scores for both groups $F(1, 63) = 135.29$, $p < .001$, $\eta_p^2 = .682$, and no statistically significant interaction with adherence $F(1, 63) = 0.66$, $p = .418$, $\eta_p^2 = .01$. The equivalence test was non-significant, $t(61.85) = -0.405$, $p = .343$, given equivalence bounds of -1.346 and 1.346 (on a raw scale) and an alpha of 0.05 (Figure 8-3). The null hypothesis was

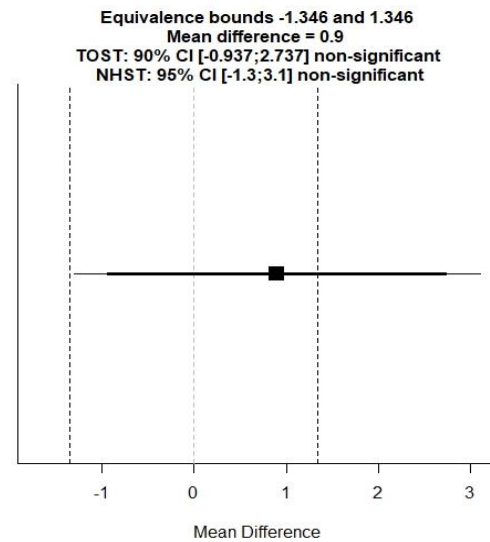


Figure 8-3. Equivalence and null hypothesis testing for CMJ

non-significant, $t(61.85) = 0.818$, $p = .417$, and an alpha of 0.05.

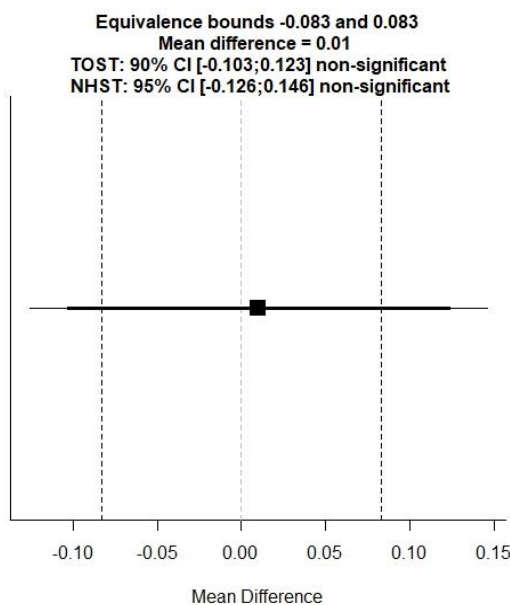


Figure 8-4. Equivalence and null hypothesis testing for RSI

There was no significant effect of the 11+Dance on RSI, $F(1, 62) = 1.45$, $p = .233$, $\eta_p^2 = .023$, but there was a significant interaction with the RSI baseline scores $F(1, 62) = 101.55$, $p < .001$, $\eta_p^2 = .621$ and not significant for adherence $F(1, 62) = 3.38$, $p = .071$, $\eta_p^2 = .052$. The equivalence testing was non-

significant, $t(57.52) = -1.072$, $p = .144$, given equivalence bounds of -0.0827 and 0.0827 (on a raw scale) and an alpha of 0.05 (Figure 8-4). The null hypothesis test was non-significant, $t(57.52) = 0.147$, $p = .883$, given an alpha of 0.05 .

There was no significant effect of the 11+Dance on the IMTP scores $F(1, 63) = 3.90$, $p = .053$, $\eta_p^2 = .058$. There was a significant interaction with the IMTP baseline scores $F(1, 63) = 128.11$, $p < .001$, $\eta_p^2 = .67$, but not for adherence $F(1, 63) = 3.65$, $p = .061$, $\eta_p^2 = .055$. The equivalence test was non-significant, $t(64.29) = -0.283$, $p = .389$, given equivalence bounds of -84.283 and 84.283 (on a raw scale) and an alpha of 0.05 (Figure 8-5). The

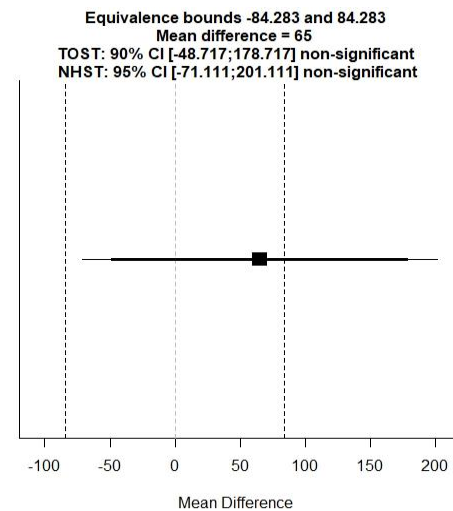


Figure 8-5. Equivalence and null hypothesis testing for IMTP

null hypothesis test was non-significant, $t(64.29) = .954$, $p = .344$, given an alpha of 0.05 .

No significant effect was observed for ASYM, $F(1, 61) = 0.002$, $p = .966$, $\eta_p^2 = .000$ and there was no significant interaction for either the pre-scores $F(1, 61) = .464$, $p = .498$, $\eta_p^2 = .008$ or adherence

$F(1, 61) = 2.096$, $p = .153$, $\eta_p^2 = .033$. The equivalence test was non-significant, $t(62.96) = 0.629$,

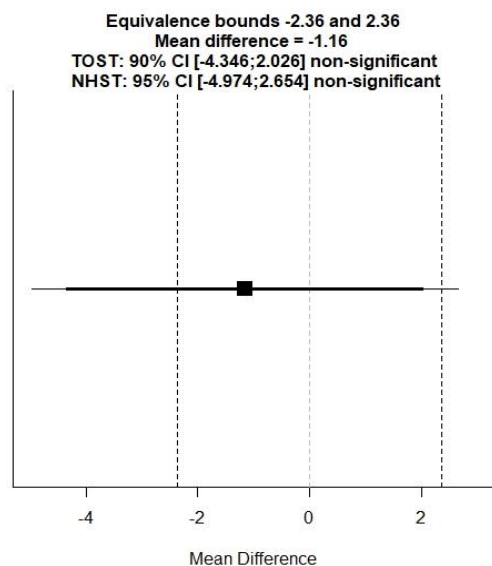


Figure 8-6. Equivalence and null hypothesis testing for ASYM

$p = .266$, given equivalence bounds of -2.360 and 2.360 (on raw scale) and an alpha of 0.05 (Figure 8-6). The null hypothesis test was non-significant, $t(62.96) = -0.608$, $p = .545$, given an alpha of 0.05 .

Based on the equivalence test and the null hypothesis test combined, it can be concluded that the observed effects for CMJ, RSI, IMTP and ASYM are statistically not different from zero and statistically not equivalent to zero.

8.4.5 Adherence

The total number of sessions for the duration of the trial ($n = 9$ weeks) was 45. Adherence for both groups was high, the 11+Dance group completed (mean \pm SD) $69 \pm 12\%$ of all sessions, whereas, for the Usual Training group completed $78 \pm 7\%$ of all sessions. The minimum number of sessions for the 11+Dance group was 11 (24%) and the maximum was 35 (78%), whereas for the Usual Training group the minimum was 24 (53%) and the maximum 37 (82%). Illness, external medical appointments and injury/pain were the main reasons for not participating in a session.

8.4.6 Injury incidence

Both groups reported dance related injuries during the trial with no statistical difference [$\chi^2(1) = 3.51$, $p = .061$]. Five dancers from the 11+Dance group and 12 from the Usual Training group. All injuries were of overuse onset and on the lower limb (Table 8-3).

Table 8-3. Injury incidence for both groups

	11+Dance		Usual Training	
	Male	Female	Male	Female
Number of injuries	0	5	5	7
Percentage of injured dancers	13.9		32.4	
Residual	-3.4		3.4	
$\chi^2 (1)= 3.51, p= 0.06, V= 0.22$				

8.5 Subgroup analysis

Baseline characteristics of the 76 participants (mean±SD, age= 12.34±.77 years; weight= 38.0±6.6 kg; height= 152.5±8.3cm; BMI= 16.2±1.6 kg·m²) are provided in Table 8-4, whereas mean differences for both groups for all the assessed parameters are presented in Table 8-5.

Table 8-4. Subgroup participants' characteristics at baseline for age, weight, height, BMI

	Overall (n= 76)			11+Dance (n= 38)		Control (n= 38)	
	Total	Male	Female	Male	Female	Male	Female
n	76	32	44	15	23	17	21
Age (years)	12.34±.77	12.25±.77	12.41±.77	12.20±.87	12.55±.75	12.29±.69	12.24±.78
Weight (kg)	38.0±6.6	39.8±7.1	36.7± 6.0	41.0±7.0	37.41±5.9	38.7±7.2	35.9±6.0
Height (cm)	152.5±8.3	151.7±9.5	153.1±7.3	153.4±8.9	154.3±7.6	150.2±10.1	151.8±7.0
BMI (kg·m ²)	16.2±1.6	17.1±1.4	15.6±1.4	17.3±1.6	15.6±1.5	17.0±1.2	15.5±1.4

Table 8-5. Subgroup baseline and post intervention mean differences for CMJ, RSI, IMTP, ASYM for the 11+ Dance and Usual Training groups

	11+Dance					Usual Training					Between groups mean difference (95% CI)
	n	Baseline (SD)	Post (SD)	Mean (SD)	† Diff %	n	Baseline (SD)	Post (SD)	Mean (SD)	† Diff %	
CMJ (cm)	35	23.4 (4.08)	26.6 (3.85)	2.88 (2.9)	↑ 14	35	23.3 (3.27)	25.1 (3.52)	1.8 (2.6)	↑ 8	1.03 (-0.28, 2.35)
RSI	35	1.00 (0.25)	1.06 (0.22)	0.06 (0.19)	↑ 6	34	0.98 (0.29)	1.11 (0.28)	0.1 (0.2)	↑ 13	-0.04 (-0.14, 0.06)
IMTP (N)	35	760 (263)	936 (227)	161 (162)	↑ 23	36	737 (235)	869 (245)	130 (169)	↑ 18	31 (-47, 110)
ASYM (%)	35	13.6 (9.49)	10.3 (9.35)	-3.44 (10.8)	↓ 24	34	11.2 (7.22)	9.55 (7.47)	-1.7 (9)	↑ 15	-1.72 (-6.6, 3.1)

$$\dagger \text{ Difference \%} = \frac{[Post-Pre]}{Pre} \times 100$$

The ANCOVA [between-groups factor: group (11+Dance, Usual training); covariate: baseline scores and adherence] revealed no significant effect of the 11+Dance on CMJ, $F(1, 66) = 3.52$, $p = .065$, $\eta_p^2 = .051$, but there was a significant interaction between the baseline and post-intervention scores for both groups $F(1, 66) = 72.5$, $p < .001$, $\eta_p^2 = .52$, and no statistically significant interaction with adherence $F(1, 66) = 0.002$, $p = .96$, $\eta_p^2 = .000$. The equivalence test was non-significant, $t(67.46) = 0.446$, $p = 0.672$, given equivalence bounds of -1.107 and 1.107 (on a raw scale) and an alpha of 0.05 (Figure 8-7). The null hypothesis test was

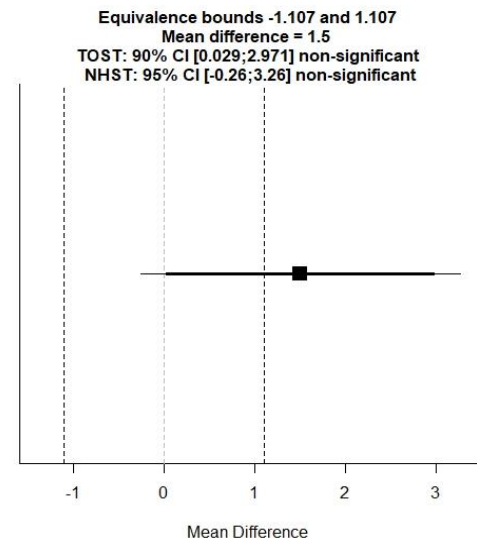


Figure 8-7. Subgroup equivalence analysis for CMJ

non-significant, $t(67.46) = 1.701$, $p = 0.094$.

The analysis showed no between groups differences for RSI $F(1, 65) = 1.02$, $p = .316$, $\eta_p^2 = .015$, but again there was a significant interaction with the RSI baseline scores $F(1, 65) = 70.21$, $p < .001$, $\eta_p^2 = .519$, but not significant for adherence $F(1, 65) = 0.206$, $p = .651$, $\eta_p^2 = .003$. The equivalence test was non-significant, $t(62.01) = 0.423$, $p = 0.337$, given equivalence bounds of -0.0758 and 0.0758

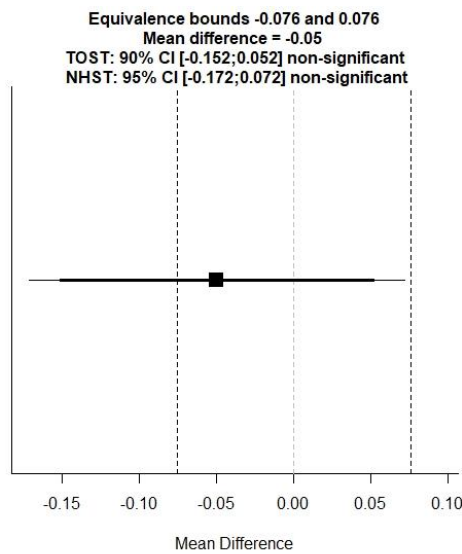


Figure 8-8. Subgroup equivalence analysis for RSI

(on a raw scale) and an alpha of 0.05 (Figure 8-8). The null

hypothesis test was non-significant, $t(62.01) = -0.821$, $p = 0.415$.

In the pre- and post-test the participants in the 11+Dance and Usual training groups had similar results in the isometric mid-thigh pull, and there were no significant difference in the change between the groups $F(1,67) = 1.7$, $p = .197$, $\eta_p^2 = .025$, but there was a significant interaction with the IMTP baseline scores $F(1, 67) = 100.14$, $p < .001$, $\eta_p^2 = .599$, but not for adherence $F(1, 67) = 1.08$, $p = .302$, $\eta_p^2 = .016$. The equivalence test was non-significant, $t(66.26) = -0.0677$, $p = 0.473$, given equivalence bounds of -70.851 and 70.851 (on a raw

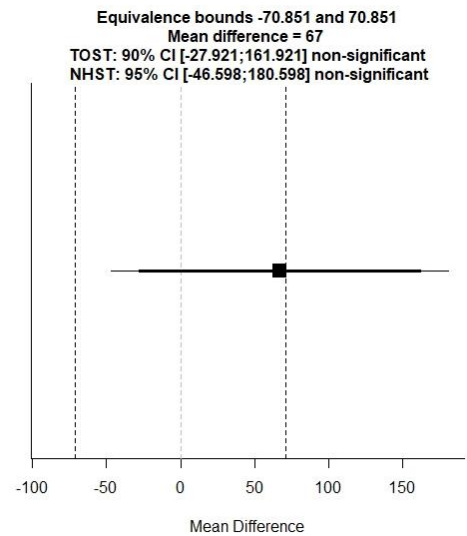


Figure 8-9. Subgroup equivalence analysis for IMTP

scale) and an alpha of 0.05 (Figure 8-9). The null hypothesis was non-significant, $t(66.26) = 1.177$, $p = 0.243$.

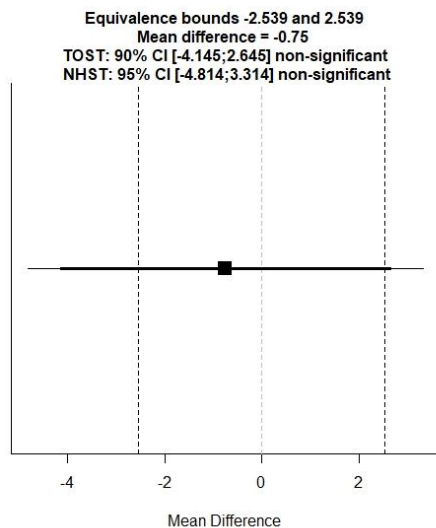


Figure 8-10. Subgroup equivalence analysis for ASYM

After the end of the intervention period, similar changes were observed in the inter-limb asymmetry in both groups. No between group differences in change were observed for ASYM $F(1, 63) = 0.109$, $p = .743$, $\eta_p^2 = .002$, with a significant interaction for the ASYM baseline scores $F(1, 63) = 7.569$, $p = .008$, $\eta_p^2 = .107$ and adherence $F(1, 63) = 2.751$, $p = .102$, $\eta_p^2 = .042$. The equivalence test was non-

significant, $t(64.62) = 0.879$, $p = 0.191$, given equivalence bounds of -2.539 and 2.539 (on a raw scale) and an alpha of 0.05 (Figure 8-10). The null hypothesis test was non-significant, $t(64.62) = -0.369$, $p = 0.714$.

Based on the equivalence test and the null hypothesis test combined, it can be concluded that the observed effects for CMJ, RSI, IMTP and ASYM are statistically not different from zero and statistically not equivalent to zero.

8.5.1 Subgroup adherence

The total number of sessions for the duration of the trial was between 35. Adherence for both groups was high, the 11+Dance group completed (mean \pm SD) $72 \pm 13\%$ of all sessions, whereas, for the Usual Training group completed $77 \pm 9\%$ of all sessions. The minimum number of sessions for the 11+Dance group was 6 (17%) and the maximum was 35 (80%), whereas for the Usual Training group the minimum was 14 (40%) and the maximum 37 (82%). Reasons for not doing the workout were: illness, medical appointment, injury or lack of time due to shorter ballet class.

8.6 Discussion

The main finding of this investigation was that no significant performance differences were observed in any of the variables tested between the 11+Dance injury prevention group, and the Usual Training group, using the exercises they would normally use before the ballet class. In addition, equivalence was not established, therefore, it cannot be stated whether the 11+Dance

is either superior or inferior to the Usual Training for the development of the selected physiological parameters. More specifically, both groups improved over time in the primary outcome (CMJ), presented similar results for RSI, and IMTP, but showed a small difference in the inter-limb ASYM, as the ASYM scores improved for the 11+Dance group but not for the Usual training group.

The subgroup analysis for the New Starters revealed similar results to the main trial and equivalence was not established. This suggests that exposure to neuromuscular training twice in a period of 24 weeks, with an eight week wash out period between, may not have had a statistically significant effect on the performance in the parameters that were assessed.

No studies appear to have examined the effects of neuromuscular training on muscular power, explosiveness, muscular strength and inter-limb asymmetry in adolescent ballet dancers, therefore, direct comparisons are not possible. Even though the mean difference of pre-post change between the two groups was not statistically significant in CMJ, the clinical significance of a 9% and 8% improvement in nine weeks, for the 11+Dance and Usual Training group respectively is not negligible. A meta-analysis (26 studies, $n = 1,024$, $n_{CMJ} = 405$) on the effect of plyometric training on vertical jump height revealed that the pooled estimate was 8.7% (95% CI 7.0 to 10.4%) (Markovic, 2007). More specifically, improvements of this magnitude were observed in recreational and competitive male and female athletes, with higher percentage improvements observed for the latter. Interestingly, the interventions utilised were of higher intensity (e.g. drop jump exercises) but not volume (i.e. foot-contacts range 450 to 2,064 and one study with 7,500) (Markovic, 2007). Diallo and associates, in their randomised controlled trial with pre-pubertal male football players reported that they utilised a combination of depth

jumps, bouncing and skipping drills with an overall total of 7,500 foot-contacts and they observed a 20% increase in jump height (Diallo et al., 2001). Interventions that include plyometric training typically consist of higher intensity jumps promoting maximal effort in order to improve jump height (Wilson et al., 1993). It is estimated that the participants of the 11+Dance performed an overall total of approximately 3,150 foot-contacts (i.e. forward and lateral landings). Even though the number of the foot contacts for the 11+Dance group was higher than most of the studies from the above meta-analysis, they were of low intensity, promoted sub-maximal effort while focusing on the quality of the movement. The low intensity of the jumping tasks of the 11+Dance together with the cues that were used (e.g. *land softly, focus on foot, knee and hip alignment*) may have limited the effect of the stimuli on maximum jump height performance. In addition, the Usual Training exercises did not involve any plyometric exercises but still showed improvements in CMJ, therefore, the power improvements in the 11+Dance group may not be related to the number of foot-contacts, but the combination of all the included exercises.

The CMJ improvement of this study are also consistent with several studies in pre-adolescent and adolescent football players that have investigated the effects of a neuromuscular-based injury prevention intervention, on physiological parameters such as the CMJ. Contrary to the results of this study, however, most of the studies revealed superior results for the intervention group with a percentage difference between 2-9% (Table 8-6). It is speculated, therefore, that the improvement in the CMJ for both groups of the current investigation may be a combination of exercise and the reduction of dance load.

Table 8-6. Studies investigating the effect of an injury prevention intervention on CMJ

	Study			Intervention			Control		
	Duration (weeks)	n	Age (SD)	Pre (SD)	Post (SD)	†Diff %	Pre (SD)	Post (SD)	†Diff %
(Rössler et al., 2016a)	10	122 (male)	10.0 (1.6)	23.0 (4.1)	24.0 (4.3)	↑ 4	22.7 (3.6)	22.9 (3.2)	↑ 1
(Pomares Noguera et al., 2018)	4	33 (male)	11.8 (0.3)	22.7 (2.9)	24.5 (5.3)	↑ 8	23.5 (2.7)	21.8 (3.2)	↓ -7
(Zarei et al., 2018)	30	82 (male)	15	41.1 (7.5)	45.0 (6.9)	↑ 9	46.7 (4.8)	47.8 (4.7)	↑ 2
(Reis et al., 2013)	9	36 (male)	17.3 (0.7)	34	36.7	↑ 8	31.5	32	↑ 2

$$\dagger \text{ Difference \%} = \frac{[Post-Pre]}{Pre} \times 100$$

Neither group revealed statistically significant change for the RSI. The observed 8% (0.07 units) and 10% (0.11 units) increase for the 11+Dance and Usual Training group respectively may not be clinically significant either. It has been suggested that decrements in RSI of 0.15 units may be a meaningful change threshold in elite junior athletes, whereas anything less than this may simply be “noise” in the data (Beattie and Flanagan, 2015). The participants performed rope skipping, a low intensity activity, in order to primarily raise the body temperature, heart and respiration rate, blood flow and joint viscosity, but also to promote a stretch-shortening-cycle stimuli (Miyaguchi et al., 2014). It is noteworthy, however, that not all the participants had the same skill level when performing this task (e.g. jumping frequency, flow of movement). It has been suggested that jumping frequency in rope skipping may affect the ground reaction force and peak force (Yamaguchi et al., 2000). The total number of the rope-skipping foot-contacts was not calculated for this trial, however, the skill variability may potentially have influenced the overall within-subject intensity and load of the stimuli. In addition, a recent rope skipping study by Garcia-Pinillos and colleagues reported

improvements in CMJ (3%, $p > .001$) and RSI (0.3%, $p > .001$) after a 10-week rope skipping training program for the intervention group (García-Pinillos et al., 2020). It is worth mentioning, nonetheless, that there were no skipping ropes at the school before the reported investigations, therefore, rope skipping was not part of the usual training prior to the beginning of this intervention (i.e. feasibility study). Two teachers utilised rope skipping in their training, which may have affected the between-groups difference, and may have been a contributing factor for the jump-height improvements in both groups. The fact that neither group improved their RSI scores, together with the lack of normative data on RSI for adolescent dancers make it difficult to judge whether the accumulation of the foot-contacts from this low intensity exercise programs was either too low or too high for this study's sample. Further investigation on the relationship of rope-skipping, muscular power and explosiveness in adolescent dancers is necessary.

The IMTP mean difference was not statistically significant for both groups at the end of the trial. The results from the between-session reliability assessment of the IMTP revealed that the smallest meaningful percentage change was 6.3%, therefore, the clinical significance of the 20% and 18% in the 11+Dance and Usual Training group respectively is worth mentioning. Even though it has been suggested that the size of the gains in strength and power are probably dependent on the assessment and the training mode being similar (Morrissey et al., 1995), the use of an isometric strength test indicates strength improvements in both groups. The only isometric exercises in both groups were the plank and its variations, whereas the rest of the exercises were dynamic, therefore, an investigation on the effect of isometric compared to dynamic strength training on muscular strength and power would be reasonable. Increases of

muscular strength have been observed in injury prevention studies, however, strength is usually assessed with isokinetic strength protocols for the quadriceps and hamstrings (Reis et al., 2013, Ayala et al., 2017a, Brito et al., 2010). Considering the high ICC and acceptable CV that the IMTP has shown, the utilisation of this test seems plausible and more feasible for further investigations on muscular strength development in young dancer.

The inter-limb asymmetry (ASYM) change difference was not statistically significant. It decreased by 27% in the 11+Dance group, whereas it increased by 12% in the Usual Training group. The mean average for both groups was <15%. It has been previously suggested that a 15% asymmetry threshold may be a critical threshold for increased injury risk prediction for both non-athlete (Barber et al., 1990) and athlete (Croisier and Crielaard, 2000, Impellizzeri et al., 2007, Grindem et al., 2011) populations. Moreover, it has been proposed that athletes returning to sport post injury should aim for asymmetries of <10% (Kyritsis et al., 2016, Rohman et al., 2015), however, even though more symmetry may be considered a successful rehabilitation marker, the 10% is an arbitrary threshold (Bishop et al., 2017). There are currently no normative data for inter-limb asymmetry and research on the association of inter-limb symmetry or lack of, with injuries is lacking in dance. It is, thus unclear whether the observed asymmetry decrease in the 11+Dance and the increase in the Usual Training group is clinically significant and needs to be investigated further.

The results of this study indicate that daily low intensity supplementary training may be inducing physiological adaptations in adolescent dancers, however, the selected test battery may not have been sensitive enough to detect all the potential changes from the exercise interventions. As it has been previously discussed in chapter 6, section 6.5 and chapter 7,

section 7.5, the delayed onset muscle soreness the participants consistently reported after participating in the 11+Dance program suggests that physiological adaptations may have occurred in the landing quality and mechanics of the jumps. The positive effects of neuromuscular training on landing kinematics have been previously reported (Myer et al., 2006, Myer et al., 2005). It has also been reported that pre-landing and landing patterns during jumping are affected by physical development, due to more effective muscle activation during the pre-activation and braking phase (Lazaridis et al., 2010). Pre-activation refers to the levels of muscle activity prior to impact or landing (Hobara et al., 2008). It has been demonstrated that hopping may affect leg stiffness through a change in pre-activation and by a concomitant change in the short-latency reflex response of the triceps surae muscles (Hobara et al., 2007). With the 11+Dance the dancers were instructed how to land and were given specific cues (i.e. *soft landing, land like a cat*) which may have affected landing biomechanics. It has been demonstrated that consistent participation in injury prevention programs can promote the reduction of vertical ground-reaction forces (DiStefano et al., 2016). Whilst speculative, it may be that the combination of all the exercises (strength, balance, plyometrics) may have promoted, a level of neuromuscular control that could not have been detected by the selected evaluation tests.

The high interaction between the baseline scores and the post intervention scores indicates a relationship, however, the lack of power due to the achieved sample size together with the a priori statistical analyses that was stated does not allow us to determine the direction of this relationship. In addition, adherence showed no significant interaction with post scores. It has been suggested that the higher the volume of neuromuscular training, the higher the

prophylactic effect (Sugimoto et al., 2014a), however, studies with neuromuscular training incorporate two or three sessions per week as part of the training sessions the participants normally have. In the 11+Dance trial, the participants trained daily, therefore, they needed to warm-up every day. Even though the selected exercises were split in two sessions and they were rotated daily, the sessions had similarities. The dosage, therefore, needs to be investigated further for optimal results.

In the absence of a true control group in the reported trial, the observed improvements for both groups raise the question whether they are due to exercise induced adaptations, the reduction of dance load ($n = 2.5 \text{ hrs wk}^{-1}$), or the combination of both. There are no studies available in the literature that investigate load manipulation, therefore, this speculation needs further investigation.

A difference in the injury incidence was observed between the two groups, even though they cannot be linked with any of the assessed physiological parameters, the 11+Dance group reported less lower-limb injuries than the Usual Training group. Neither the length of the study nor the sample size was appropriate for this observation to be generalised about the effectiveness of the 11+Dance as injury prevention intervention. Based on a systematic review (9 studies, $n = 13,503$ participants) on the effect of neuromuscular warm-up, to provide the greatest potential for the reduction of injuries, the duration of the training needs to be longer than three consecutive months (Herman et al., 2012). The 11+Dance, therefore, needs to be assessed longitudinally and with a larger sample with regard to its potential to reduce injury incidence.

It has been suggested that without performance-enhancement training effects, athletes may not be motivated to participate in neuromuscular training programs (Myer et al., 2005), therefore, given the existing evidence on the positive effects of strength and neuromuscular training on the reduction of injury incidence the use of validated surrogate outcomes in injury prevention research in sports is reasonable. A surrogate endpoint or outcome, is often used as a proxy for clinical trials, as it enables smaller, faster and thus cheaper trials to be conducted (Svensson et al., 2013). This investigation utilised validated outcomes and no direct comparisons were made with different populations other than the selected one.

Contrary to sports, dance training is not driven by physiological parameters such as maximum jump height, or muscular strength development, whereas movement proficiency is the ultimate aim. Whilst improving physiological parameters has anecdotally been the current trend for the dance industry, this thesis has previously discussed (see chapter 2, section 2.8.1) that the relationship of such parameters and injury incidence is not clear through the existing literature. This makes the examination of surrogate outcomes in dance even harder due to the potential existence of the “surrogate paradox”, which occurs when the effect of the treatment on the surrogate (muscular strength and power) is in the opposite direction of the effect of the treatment on the outcome of interest (injury incidence) (VanderWeele, 2013). Thus, the short duration of this trial, together with the lack of power for this investigation do not make the exploratory assessment of injury incidence a very informative outcome. However, even though the results of this study support the null hypothesis, equivalence was not established and the 11+Dance did not cause any harm. Based on the aforementioned studies on neuromuscular

injury prevention interventions, it is possible, that with a larger sample size the results may have been statistically significant.

8.6.1 Strength and limitations

This is the first randomised controlled trial to investigate the effects of neuromuscular training on selected physiological performance responses in adolescent dancers. All sessions were supervised in order to ensure intervention fidelity, however, effort and motivation are factors that cannot be controlled easily with bodyweight exercise.

Although the current study is novel in several aspects, such as randomisation, blinding of assessment, standardised intervention protocol, and statistical analyses when interpreting the results, practitioners should be aware of some identified limitations. The assessed intervention (11+Dance) was compared against four different types of exercise programs, but all four programs were grouped as Usual Training, it is thus difficult to identify which of these combinations were more or less effective against the 11+Dance workout. In addition, the recruitment of the necessary sample to achieve the desired power was not possible due to the trial being in an applied setting, therefore, based on the null hypothesis testing the reported results may be giving a false negative (Type II error) outcome.

8.7 Conclusion

The results of this study reveal that in the short term, the 11+Dance elicited similar effects with the Usual Training workouts on the selected parameters, however, equivalence was not established. Muscular power and strength improved for both groups, therefore, low intensity

supplementary training may need to be part of dance training, to compliment the development of the young dancer. No negative side effects were observed for the 11+Dance and adherence was high as the training was incorporated in the existing load, therefore, the 11+ Dance injury prevention intervention may be utilised to complement existing practice. Larger longitudinal studies are needed to investigate the efficacy of the 11+Dance on injury incidence and severity.

9 Strengths, limitations and future research

The results of the present thesis are relevant and important to the dance science literature, as they have been extracted from strict clinical methodological protocols. The systematic review was conducted and reported based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The cross-sectional investigation replicated a methodologically robust epidemiological study, whilst adding evidence in the relationship of injuries, physiological and non-invasive biological markers. Conducting a randomised controlled trial in an applied setting, such as a vocational ballet school, is challenging and is accompanied by certain difficulties (e.g. recruitment, length of the study, tradition). This thesis, however, has demonstrated that it is feasible to conduct methodologically robust trials typically found in clinical practice. All trials were reported according to the CONSORT statement guidelines.

The epidemiological report was based on part of the year data and not a complete season, a factor that needs to be taken into consideration when interpreting the reported results. Also, the cross-sectional design of the study in chapter 5 does not allow a cause-effect outcome, and

potential confounding factors (e.g. previous injury history, exact dance exposure) could not be fully controlled.

Although the participants were randomly assigned, by an independent researcher, to either the intervention and the control group, recruitment for the pilot and main trials was limited to the younger students of the school as there was more flexibility both from the participants (students and teachers) but also from the school's schedule. The confounding factors, such as age and dance experience, may have affected the results. Since all trials were based in the same centre, potential intervention contamination cannot be excluded with certainty, both between the students in the intervention and usual training group but also between the dance teachers and the principal investigator. Also, in the absence of a true control group, it is difficult to assess the effect of the dance-only approach, on muscular strength and power.

Lastly, it is worth noting that, in research bias can take different forms, conscious and unconscious (Hammersley and Gomm, 1997). This investigation was tailored to produce findings to serve no other goal other than knowledge. Even though the study is advocating strength training and in particular neuromuscular training, it is based on current robust evidence but no preconceived conclusion. It has been my primary responsibility that all necessary and possible measures have been taken to protect the integrity and transparency of this investigation.

Future studies are needed to validate the results of this study. The conceptual model presented in chapter 4 section 4.5, needs to be validated for adolescent dancers, in order to establish the neuromuscular potential of the dance-only training approach. Considering the lack standardised interventions for injury risk management and prevention, the 11+Dance is

opening a new chapter in the literature. The efficacy thus of the 11+Dance on injury incidence is currently being assessed longitudinally and with a larger cohort, before a potential implementation strategy is formulated and applied.

10 General Discussion

The development of the overall methodology of this PhD was based on methodologically robust approaches that are currently used in clinical practice. A step-by-step approach was used, whereby each step was informing the following. This thesis evolved from the initial investigation of growth, maturation and overuse injuries in aesthetic sports/activities. The synthesis and analyses of the data was systematically done based on the PRISMA guidelines. Even though there were 19 out of 23 studies reporting a positive association of growth, maturation and injuries the study design (i.e. cross-sectional), and the high risk of bias it was not possible to extract any robust conclusions about these associations in dance. Moreover, six studies reported an association of training load and overuse injuries but only half of these studies revealed an association of growth maturation and overuse injuries. The large variation of the reported training load (i.e. dance hours per week), however, made the results inconclusive.

The equivocal results of the review led to the investigation of the relationship between injury incidence and muscular power (countermovement jump), together with the potential gender and maturity status differences. This longitudinal cross-sectional study revealed no association between injury incidence neither with muscular power nor with gender or maturity status.

Based on the current literature in youth sports a link between neuromuscular control and injuries was speculated which led to a randomised controlled trial to evaluate the feasibility of a trial on the effects of neuromuscular training in adolescent dancers. The investigation in the literature of neuromuscular training led to the development of the 11+Dance, the first ever neuromuscular injury prevention intervention tailored for dancers.

The 11+Dance program is an adaptation of a well-established injury prevention intervention called FIFA 11+. The feasibility study provided this investigation with valuable information in order to conduct a randomised controlled pilot trial with a primary aim to perform power and sample size calculations. The results of the pilot trial informed the main trial, however, the desired sample size was not achieved, therefore, the trial was underpowered. The aim of the main trial was to evaluate the effect of the 11+Dance on muscular power, explosiveness, muscular strength and inter-limb imbalance, compared to the Usual Training group. The findings of the main trial were inconclusive, as the 11+Dance group did not show statistically significant differences in either the primary or secondary outcomes, however, equivalence was not established. An exploratory analysis of the injury incidence during the length of the trial indicated less injuries for the 11+Dance group than the Usual Training group. The lack of power together with the short length of the trial need to be taken into consideration when interpreting these findings.

Even though the results of this study are inconclusive, the approach of this investigation is as evidence-based as possible, therefore, this work is not recommending a model of training in replacement of the existing model, but the initiation of change towards a safer training environment for the young dancer. Therefore, the inclusion of neuromuscular training should

not necessarily be at the exclusion of any other type of training (i.e. usual training), however, considering the current body of literature both in quantity and quality on the prophylactic effects of neuromuscular training on injuries in youth sports makes the use of the 11+Dance workout reasonable as the reported results do not indicate any harm. The efficacy of the 11+Dance on injury incidence is currently being investigated in a controlled trial with a larger sample in the U.K.

The use of surrogate measures in injury prevention research in sports is well established, therefore, this work may be considered as a starting point for further research that focuses on injury prevention in pre-professional dancers. Considering the high prevalence of injuries that is presented in the review of the literature and that was established with this investigation, it is both reasonable and ethical for researchers and practitioners to investigate further established methods (such as neuromuscular training) that may minimise associated injury risk factors and may have a prophylactic effect against both traumatic and overuse injuries in pre-professional and professional dancers.

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12 Appendices

12.1 Risk of Bias Assessment (RTI-IB)

	Selection bias confounding		Detection bias		Detection bias confounding		Selective outcome reporting		Confounding			
Risk of Bias assessment Questions	Q2: Does the strategy for recruiting participants into the study differ across groups?	Explanation for rating	Q5: Was the assessor not blinded to the outcome, exposure, or intervention status of the participants?	Explanation for rating	Q6: Were valid and reliable measures not used on not implemented consistently across all study participants to assess inclusion/exclusion criteria, intervention/exposure outcomes, participant benefits and harms, and potential confounders?	Explanation for rating	Q9: Are any important primary outcomes missing from the results?	Explanation for rating	Q11: Are results believable taking study limitations into consideration?	Explanation for rating	Q13: Were important confounding variables not taken into account in the design and/or analysis (e.g. through matching, stratification, interaction terms, multivariate analysis, or other statistical adjustment such as instrumental variables)?	Explanation for rating
Study Amaral et al. (2012)	Yes, differs	<i>One participant has been selected even though she already had menarche (p.</i>	Yes, not blinded	<i>Not determined in the paper</i>	Yes, valid and reliable measure used	<i>Skeletal maturation - Tanner-Whitehouse TW3. Maturation level - questionnaires (p.395). Radiographs according to Hanfer et al and Claessens et al. Handgrip tested with dynamiter (p.396)</i>	No important outcome(s) missing	<i>Association between Ulnar Variance and skeletal age was noted (r=0.38; p<0.05) (p.399)</i>	No, not believable	<i>The outcomes are not discussed in line with the limitations of the study. No odds ratio reported</i>	Partially: some variables taken into account or adjustment achieved to some extent	<i>Not all confounders are considered</i>

(cont.): Risk of bias assessment (RTI-IB)												
Caine, Cochrane et al. (1989)	Not applicable: one study group	<i>n/a</i>	Yes, not blinded	No blinding was used for the assessments	Yes, valid and reliable measure used	<i>Interviews and medical files (p.813)</i>	No important outcome(s) missing	<i>All important outcomes listed (p.816)</i>	Yes, believable	<i>The authors state that the outcomes may not be representable due to the limitations (p.819)</i>	No: taken into account	<i>n/a</i>
Carter and Aldridge (1988)	Not applicable: one study group	<i>n/a</i>	Yes, not blinded	<i>No blinding was used for the assessments</i>	Yes, valid and reliable measure used	<i>Radiographic investigation for injury and maturation, references stated (p.834)</i>	Cannot determine	<i>There is no methods. No statistical analysis</i>	No, not believable	<i>Confounders not considered, nor limitations. Results based on opinion and personal communication (p.836) - No odds ratio reported</i>	Yes, not accounted for or not identified	<i>Confounders not considered</i>
Carter et al. (1988)	Not applicable: one study group	<i>n/a</i>	Yes, not blinded	<i>No blinding was used for the assessments</i>	Yes, valid and reliable measure used	<i>Radiographic investigation for injury and maturation, references stated (p.110)</i>	Yes, important outcome(s) missing	<i>No statistical analysis</i>	No, not believable	<i>Confounders not considered, nor limitations. No odds ratio reported</i>	Yes, not accounted for or not identified	<i>Confounders not considered</i>
Chang et al. (1995)	No, does not differ	<i>Both groups were students of the Chinese Opera school (p.861)</i>	No, blinded	<i>the plain radiographs were reviewed by two authors independently without knowledge of the questionnaire results (p.861)</i>	Yes, valid and reliable measure used	<i>Blinded radiographic examination and survey. However, the validity of questionnaire is not mentioned</i>	No important outcome(s) missing	<i>All important outcomes listed (p.862)</i>	Yes, believable	<i>Relative risk reported (p.862) however no limitations reported, nor all confounders considered</i>	Yes, not accounted for or not identified	<i>Confounders not considered</i>

(cont.): Risk of bias assessment (RTI-IB)												
Goldstein et al. (1991)	Cannot determine	n/a	No, blinded	...radiologist...who had no knowledge of the patient history (p.463)	Yes, valid and reliable measure used	Blinded MRI investigation	No important outcome(s) missing	Table 2. Age/MRI results relationship (p= 0.005) (p.467)	Yes, believable	All important outcomes reported	No: taken into account	No statistical statement could be made regarding the rate of injury...(p. 465)
Kolt (1999)	No, does not differ	Participants were drawn from 17 centres (p. 313)	Yes, not blinded	No blinding was used for the assessments	No, valid and reliable measure not used	Methodology not fully justified. Prospective survey but information was collected at 3 months intervals...(p. 317)	Yes, important outcome(s) missing	P values of growth plate injuries	Yes, believable	Limitations through self-reported data and the participation of the coach in the recording of the data justified (p. 317)	No: taken into account	The differences between elite and sub-elite are given
Lindholm et al. (1994)	Yes, differs	Investigation group not randomly selected	Yes, not blinded	No blinding was used for the assessments	Yes, valid and reliable measure used	Tanner stages, skinfold, hormonal analysis (p. 270)	Yes, important outcome(s) missing	Association of age and menarche is not reported	Yes, believable	The results are in line with previous evidence, however limitations are not discussed	Cannot determine	n/a
Maffulli et al. (1992)	No, does not differ	Both experimental and control group were visiting the investigator	Yes, not blinded	Not blinded during the follow up	Yes, valid and reliable measure used	Radiographs	Yes, important outcome(s) missing	No statistical analysis	No, not believable	Only the experimental group was followed, no statistical reference of results. No odds ratio reported	Yes, not accounted for or not identified	No confounding variables taken into account

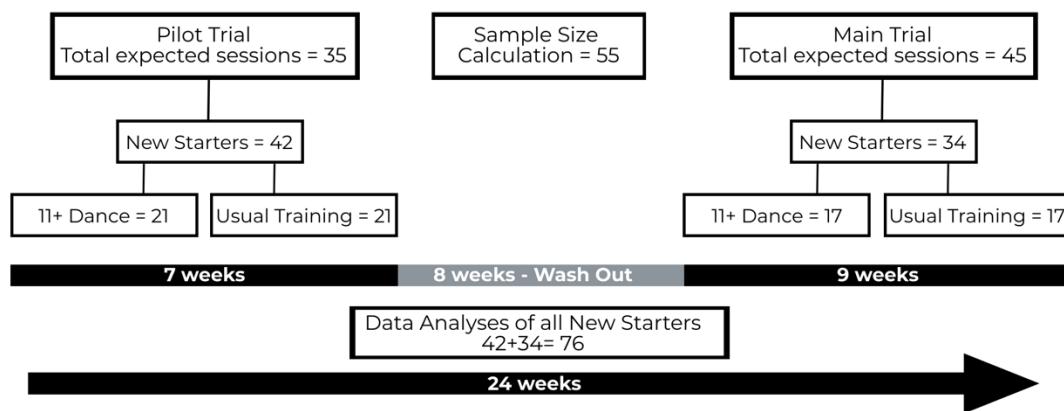
(cont.): Risk of bias assessment (RTI-IB)												
Purnell et al. (2010)	Yes, differs	<i>Different inclusion criteria used for different ages (p.42)</i>	Not applicable: assessor cannot be blinded	<i>Retrospective survey</i>	No, valid and reliable measure not used	<i>Safe Dance Injury Survey modified but not tested for reliability (p. 42)</i>	No important outcome(s) missing	<i>All important outcomes reported</i>	Yes, believable	<i>Limitations reported</i>	Partially: some variables taken into account or adjustment achieved to some extent	<i>Sensitivity analysis</i>
De Smet et al. (1994)	Cannot determine	<i>...and compared with a matched group (p.847)</i>	No, blinded	<i>All measurements were done by a single observer (p.846). Blinded process not stated</i>	<i>Yes, valid and reliable measure used</i>	<i>Blinded radiographic examination and survey</i>	No important outcome(s) missing	<i>All important outcomes reported</i>	No, not believable	<i>Confounders not considered, nor limitations. No odds ratio reported</i>	Cannot determine	<i>n/a</i>
Bowerman et al. (2014)	Not applicable: one study group	<i>n/a</i>	Yes, not blinded	<i>No blinding was used for the assessments</i>	No, valid and reliable measure not used	<i>Growth was assessed by change in foot length (Aml, Peker, Turgut, & Ulukent, 1997; Krishan & Sharma, 2007) (p.235). (PI: protocols not applicable for the purpose of the research)</i>	No important outcome(s) missing	<i>All important outcomes listed (p.237)</i>	No, not believable	<i>Even though limitations are discussed, the protocols used for maturation assessment are not appropriate</i>	Cannot determine	<i>n/a</i>
Steinberg, Siev-Ner (2011)	Not applicable: one study group	<i>n/a</i>	Not applicable: assessor cannot be blinded	<i>n/a</i>	Yes, valid and reliable measure used	<i>Interview, screening, clinical examination, x-ray (p. 48)</i>	No important outcome(s) missing	<i>All important outcomes reported</i>	Yes, believable	<i>Odds ratio reported, limitations reported</i>	Partially: some variables taken into account or adjustment achieved to some extent	<i>Survival analysis performed (p. 48)</i>

(cont.): Risk of bias assessment (RTI-IB)												
Steinberg et al. (2013)	Not applicable: one study group	<i>n/a</i>	Not applicable: assessor cannot be blinded	<i>n/a</i>	<i>Yes, valid and reliable measure used</i>	<i>Medical examinations by the same orthopaedic, interviews and anthropometric data</i>	No important outcome(s) missing	<i>All important outcomes reported</i>	Yes, believable	<i>Limitations reported</i>	Cannot determine	<i>n/a</i>
Warren et al. (1991)	Yes, differs	<i>Volunteers from dance companies, schools, advertisements and referrals (p. 848)</i>	Yes, not blinded	<i>No blinding was used for the assessments</i>	Yes, valid and reliable measure used	<i>Medical and endocrine examination, anthropometric data, Hormonal, bone density, radiographic confirmation of stress fractures (p. 848)</i>	No important outcome(s) missing	<i>All important outcomes listed (p.237)</i>	Yes, believable	<i>The limitations are not discussed, but results in line with existing knowledge</i>	No: taken into account	<i>Confounders are considered</i>
Kadel (1992)	Cannot determine	<i>n/a</i>	No, blinded	<i>Assessors did not select the participants</i>	Yes, valid and reliable measure used	<i>Prospective survey, references for methodology given (p. 445)</i>	Yes, important outcome(s) missing	<i>P value for age/stress fractures is not reported</i>	Yes, believable	<i>Limitations discussed (p. 448). Odds ratios reported (p.446)</i>	No: taken into account	<i>Logistic regression analysis (p.446)</i>
Steinberg et al. (2014)	Not applicable: one study group	<i>n/a</i>	Not applicable: assessor cannot be blinded	<i>n/a</i>	<i>Yes, valid and reliable measure used</i>	<i>Longitudinal survey</i>	No important outcome(s) missing	<i>All important outcomes reported</i>	Yes, believable	<i>Limitations reported</i>	Cannot determine	<i>n/a</i>

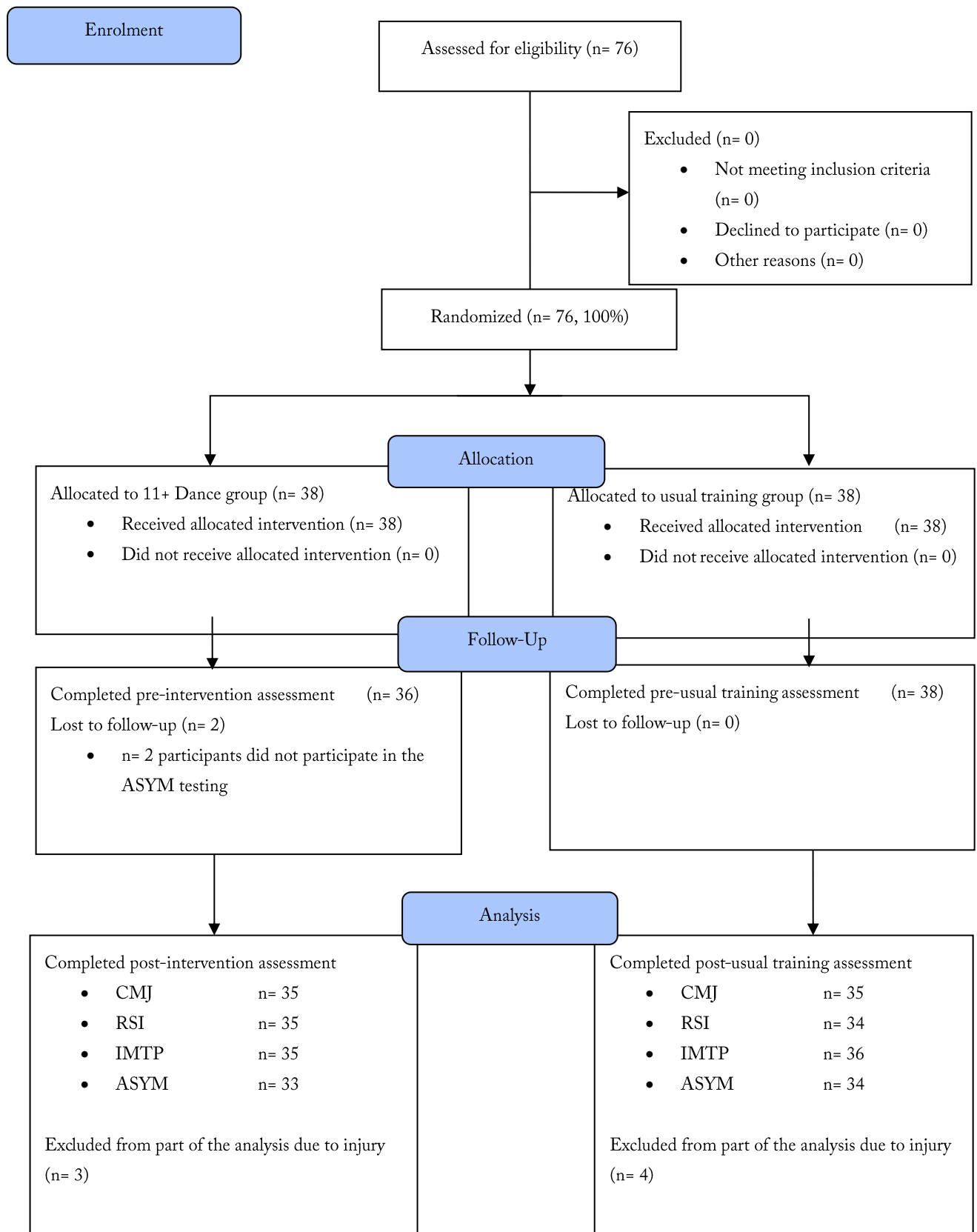
(cont.): Risk of bias assessment (RTI-IB)												
Steinberg, HersHKovitz et al. (2011)	Not applicable: one study group	n/a	Not applicable: assessor cannot be blinded	n/a	Yes, valid and reliable measure used	Physical examination of participants (p.1116), however the investigators probed the dancers with questions regarding pain (p.1116)	No important outcome(s) missing	All important outcomes listed (p.237)	No, not believable	Investigators were searching for a specific pathology and not simply screening the participants	Cannot determine	n/a
Baranto et al. (2006)	Cannot determine	Even though this is a single group study, there is no information on why this particular population was selected "...the highest possible ranking" (p908)	Yes, not blinded	No blinding was used for the assessments (i.e. blinded assessor for MRI)	Yes, valid and reliable measure used	MRI scans (p.908), Self-Assessed, Oswestry Disability Questionnaire, neurological examination (p.909) References for all apart from the Oswestry Q. However, higher specification scanner for the follow up (p.908)	Yes, important outcome(s) missing	No statistical analysis of repeated measures (p.910)	No, not believable	Limitations discussed but important data is missing, and methodological discrepancies are not taken into consideration. (p.913)	Cannot determine	n/a
Loud et al. (2005)	Not applicable: one study group	n/a	Not applicable: assessor cannot be blinded	n/a	Yes, valid and reliable measure used	GUTS survey of identified mothers who were nurses. Self-reported data collection of large sample (p. 400)	No important outcome(s) missing	All important outcomes reported	Yes, believable	Survey was done on a large population. Odds ratio reported. Limitations discussed thoroughly (404-5)	Partially: some variables taken into account or adjustment achieved to some extent	Adjustment for age... (p. 401)

(cont.): Risk of bias assessment (RTI-IB)												
Micheli and Fehlandt (1992)	Not applicable: one study group	<i>n/a</i>	Not applicable: assessor cannot be blinded	<i>Retrospective medical data</i>	<i>Yes, valid and reliable measure used</i>	<i>Survey</i>	Yes, important outcome(s) missing	<i>Injury prevalence is discussed but not statistical analysis</i>	Yes, believable	<i>An estimation of injuries is discussed but no odds ratio reported, and limitations are not discussed</i>	Cannot determine	<i>n/a</i>
Thein-Nissenbaum et al. (2012)	No, does not differ	<i>Researchers clearly define inclusion process (p. 75)</i>	Not applicable: assessor cannot be blinded	<i>n/a</i>	Cannot determine or measurement approach not reported	<i>Questionnaire is stated to be reliable but with no references (p. 75)</i>	No important outcome(s) missing	<i>All important outcomes listed</i>	No, not believable	<i>Limitations reported, however the reliability of the research tool is not reported</i>	Cannot determine	<i>n/a</i>

12.2 Trial flowchart for New Starters from the pilot and main trial



12.3 New starters trial flowchart



12.4 Ethical approval for the cross-sectional study

From: [REDACTED]
Subject: Institute of Sport - Ethics Approval Notification
Date: October 10, 2016 at 10:00
To: Kolokythas, Nicolas [REDACTED]
Cc: Wyon, Matthew (Prof) [REDACTED]



Message sent on behalf of [REDACTED]

Dear Nico,

The review panel for ethics in sports research has now considered both of your recent submissions. The panel have approved your projects and wish you every success in the completion.

Kind regards

[REDACTED]

[REDACTED]
Research Administrator
Faculty of Education Health and Wellbeing
University of Wolverhampton
Walsall Campus, Gorway Road
WALSALL WS1 3BD

Tel: [REDACTED]
[REDACTED]

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12.5 Ethical approval for the randomised trials

From: [REDACTED]
Subject: Institute of Sport - Ethics Outcome Notification
Date: May 17, 2017 at 15:25
To: Kolokythas, Nico [REDACTED]
Cc: Wyon, Matthew (Prof) [REDACTED]



Message sent on behalf of [REDACTED]

Approved - Submission 117474 Title: "The effect of neuromuscular warm-up on power, strength and balance in young ballet dancers: a randomised controlled trial"

Dear Nico,

The review panel for ethics in sports research has now considered your recent resubmission. The panel have approved your project and wish you every success in its completion.

Kind regards,

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

You can book a meeting via:
<http://sams.wlv.ac.uk/>